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DIRECT DIGITAL CONTROL OF A MARINE DIESEL PROPULSION PLANT.

Peter Bruce Bowman

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DIRECT DIGITAL CONTROL OF A MARINE DIESEL PROPULSION PLANT

by

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B.E.E., Cornell University

(1960)

SUBMITTED IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS

FOR THE DEGREE OF

OCEAN ENGINEER

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May, 1973

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DIRECT DIGITAL CONTROL OF A MARINE DIESEL PROPULSION PLANT

by

PETER B. BOWMAN

Submitted to the Department of Ocean Engineering in partial fulfillment of the requirements for the degree of Ocean Engineer.

ABSTRACT

A method to control a large bore, slow speed diesel engine utilizing a digital computer has been developed. The particular engine selected for the study was of the direct drive reversing type coupled to a fixed-pitch propeller.

In order to control a propulsion plant and avoid a costly experimental program, one must be able to model the plant. Adequate models for this purpose have been developed by others, except that no models for reversing a diesel engine with a fixed-pitch propeller were found in the literature. Therefore, a model for reversing the slow speed engine was constructed. Computer simulation was carried out on the Interdata 70 and IBM 1130 computer facilities at M.I.T. utilizing the Dynamic System Simulation Program (DYSYS) developed by the Department of Mechanical Engineering.

A hardware survey covering sensors, signal processors/converters, mini computers (process control), actuators, and display devices was conducted. From the results of this survey, equipment for control of an actual engine could be selected.

A scheme for control of the engine was constructed and carried out to the logic flow diagram level. An estimate of the computer size needed to accomplish the control process was made. In addition, a brief discussion of problems associated with automation and the state of the art was also included.

Thesis Supervisor: A. Douglas Carmichael
Title: Professor of Power Engineering

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CHAPTER I.

INTRODUCTION

1. Background

A. Automatic Control as an Aid to the Maritime Community

Automatic controls bring several possible advantages to the ship owner/operator:[1]

(1) Improved conditions for the crew by transferring tedious repetitive work to automatic operation.

(2) Savings due to more efficient use of the crew; i.e., by transferring personnel from watchkeeping to day work, more overall maintenance work may be performed.

(3) An increase in the availability of the ship due to an improved degree of operation and maintenance.

(4) Savings in operating costs due to improvements in the efficiency of the machinery.

(5) Reduced ship manning levels.

(6) More rapid sensing, alarming and rectification of propulsion plant maloperation.

The word possible is stressed because the above are potential advantages and become reality only when automatic controls are properly applied and utilized. It is obvious that automatic control when it is not necessary or even desirable will lead to different results.

B. Why Digital Control?

Shipboard automatic control systems in the past have generally been of the pneumatic, hydraulic, electric or combination type. The control loops and

alarms usually associated with these schemes have generally consisted of isolated systems operated by variations in only one parameter, for example, cooling water temperature, or lubricating oil pressure. A need exists for coordination of these isolated systems. Two basically different methods for accomplishing this are analog and digital.

Analog systems have been used extensively in the past and abound in nature; most propulsion plant control parameters such as pressure, temperature, level, etc., are analog in nature. Practically speaking, there are many more analog than digital transducers. However, extremely precise, large, spread out analog systems are generally not seen. Logging of analog systems is by strip chart recorder, and although simple to operate and economical, logging of a large number of inputs can be cumbersome, and data reduction and retrieval is difficult.

Most of these shortcomings are eliminated by using digital control systems. Digital signals are easily transmitted for greater distances than analog signals, and although their logging systems may be more complex than the strip chart, this is overshadowed by the ease of information retrieval. Digital logging of hundreds of input signals such as might be required in a complex control system can be accomplished by digital equipment at much less cost than with strip recorders.[2]

Once digital logging equipment has been installed in ships, as it is widely being done today, then "...the natural step forward...is computer control, either in a simple form in which conventional control loops are retained and certain remedial actions are instigated by the computer when an alarm

condition occurs, or in a more comprehensive form in which the computer takes over the duties of the separate control loops." [3] Additional reasons for the "natural" step to computer control are the increasing size and complexity of modern propulsion plants, and the benefits accrued by searching for maximum efficiency realizing that small percentage changes in the uses of large masses of capital equipment can yield significant savings in operational costs. [4]

As mentioned previously, most propulsion plant parameters are analog in nature, and at first glance since digital transducers at competitive prices are not readily available, this might pose a problem. However, this potential trouble area is eliminated by the large number of analog to digital (A/D) and digital to analog (D/A) converters that are available to the systems engineer.

Direct digital control, where the digital computer performs the control calculations, gives the control engineer the greater design flexibility (he is not tied down to conventional controllers), and control performance can be improved (there is no effective limit to the precision of digital computation). [4A]

Digital computers can also be applied in a variety of areas of the ship other than the machinery area. For example: [5,6]

(1) Loading/unloading operations: to minimize turn-around time; reduce manning requirements; issue documentation; monitor tank levels and environment.

(2) Navigation: route planning; fixes and other calculations; collision avoidance; steering control.

(3) Administration: statistical analyses; record keeping; stock/inventory control; payroll.

(4) Other: strain calculations; stability calculations.

C. Historical Development/State of the Art

1. Automatic Control in General

Automatic control of ships systems utilizing a digital computer is still a new technique, and only slightly older is automatic control of shipboard machinery in general.

For a number of years, automatic controls have been successfully applied in a variety of industries. The maritime community, until very recently, however, has not been as "progressive" as its land-based counterparts. As early as 1960 the principles of automatic controls were well known to designers and engineers in the marine field, but it took five years before any significant portion of new construction or even designs for ships not yet built had sufficient automation features for unattended machinery spaces to be considered. According to at least one authority,[7] the reasons for this delay were:

(1) Control equipment offered the marine industries had been primarily developed for land installations, and when subjected to heat, vibration, and humidity of the magnitude found in shipboard machinery spaces, many instruments failed and modifications were needed.

(2) Compared with the land market, the marine industry's needs were small and many control system manufacturers simply turned their attention toward brighter prospects.

(3) A reluctance of marine engineers to foresee the ultimate use of controls engineering aboard ship; i.e., the unattended machinery space.

(4) Doubts by the marine community as to the reliability of automatic controls.

(5) Governmental authorities and societies were slow to react to progress made in automatic controls, and required that engineers should spend a certain number of years in engine rooms prior to certification. (It had always been done that way!)

Thus there were both technical and psychological barriers to overcome before automatic control could become a universally accepted reality. Through the 1960's both these problems were gradually overcome.

Although isolated individual components had earlier had automatic controls, in 1961 when the Mitsui-built KINKASAN went to sea it was correctly hailed as the first automated ship.[8] This ship displaced 9700tdw and was propelled by a 12,000 bhp Burmeister and Wain low speed diesel with three auxiliary diesel generators for electrical power. Her auxiliary boiler had automatic combustion controls and feedwater regulation. Other features included: bridge control of the main engines; automatic recording of cylinder liner and exhaust gas temperatures and orders on the engine telegraph. The main air compressors and fuel oil transfer pumps stopped automatically, and fuel oil temperature was automatically controlled. Cooling water valves for the diesels were remote controlled by the watchkeeper from an air conditioned, soundproofed control room.

By 1963, awareness of automatic controls had increased and a significant number of papers on the subject were being read before institutions devoted to the advancement of marine engineering. At this stage, although it

was acknowledged that automatic controls enabled the numbers of watchkeepers to be reduced, no attempt to coordinate and rationalize automatic controls for unattended operation of the machinery spaces was reported.

In 1964 the East Asiatic Company's ANDORRA put to sea and operated at night with an unattended machinery space; this ship was followed shortly by several others. Their features included thermostatically controlled cooling systems, automatic engine shutdowns on failure of the lubricating oil system, automatic control of auxiliary machinery, and comprehensive alarm systems including bilge level and fire alarms that operated on the bridge and in the engineer's accommodations.[9]

After 1966, automatic controls spread rapidly. The sound isolated, air conditioned control room became common. Data logging equipment began to be used, including features which: (1) automatically operated alarms for off-limit readings; (2) periodically printed readings and also on demand; (3) continuously scanned all or at least vital points.

The widespread use of controls first appeared in diesel-powered ships for two reasons; first, it is more difficult to apply automatic controls successfully to the complex combination of boilers, turbines and steam/feed systems, and secondly, before 1960, oil engines dominated commercial propulsion. The first significantly automatically controlled steam plant was installed in the RYOYO MARU in 1965. She had a 20,000 shp low head steam turbine and utilized a television system which enabled one engineer and one rating to operate the plant. Bridge controls were not fitted, but other controls included: (1) hydraulic control of the turbines; (2) pneumatic operation of the turning

gear from the control room; (3) automatic lube oil temperature and gland steam pressure control; (4) automatic combustion and burner ignition control; (5) auto starting emergency diesel generator as well as other essential auxiliaries.[10]

Bridge controls were installed in subsequent steam-propelled ships and the use of automatic controls spread as in the diesel case. By mid-1969, 23 steam turbine as well as 205 diesel ships qualified for the UMS designation by Lloyds Register of Shipping.[11]

2. Digital Computer Control

In the early 1960's digital computers first began to be used extensively for industrial equipment monitoring and process control, especially in the chemical, electrical power generating and steel industries. As in the case of general automatic control, marine applications of direct digital control lagged behind largely because first, "...until recently (i.e., the latter half of the 1960's) there has been no equipment compact enough, cheap enough, reliable enough and powerful enough in its control capability to be economically used aboard ship, ...(and second,) user attitudes...." By 1965, however, feasibility studies were being made to apply computer methods to ships.

The first use of a digital computer aboard a ship was probably on the refrigerated cargo ship POLAR ECUADOR and her five sister ships built by Blohm and Voss for temperature control of the cargo holds and monitoring of the engine room and refrigerating machinery. In 1968 the refrigerated cargo ship AQUILON, built in Belgium, was fitted with a computer, which in addition to the above, performed logging functions and navigation calculations,

and provided warnings of potential collisions.[12]

In 1969, the QUEEN ELIZABETH II was provided with a digital computer whose purpose was to control the ship's fresh water generating plant, and condenser vacuum as well as monitoring main and auxiliary equipments and performing stock control functions for the ship's hotel services.[13]

An important development in computer controls was the 210,000dwt tanker SEA SOVEREIGN which entered service in late 1969. Built by the Swedish firm of Kockums, control loops for boiler automatic combustion, water level, superheated steam temperature, and main turbine gland steam pressure, together with certain controls on the steam generator and deaerator were included. These functions could also be performed conventionally, and the computer was also capable of performing navigational calculations, course prediction, autopilot steering, and limited cargo handling control. The ASEA "Turbodac" program and System 1700 (24K work memory) process control computer provided:

(1) alarm monitoring of machinery

(2) trend calculations and recording

(3) alarm printout

(4) data logging; printout every four hours and on demand

(5) bridge control of main machinery

(6) maneuvering log

(7) "economic monitoring" of machinery to achieve "optimum conditions."[14]

The British build 900dwt sludge carrier GLEN AVON has been operating with an unattended machinery space and without an engineer aboard! The M2112 computer with a memory capacity of 4096 words (16 bits per word) provides

multi-interrupt capability, scanning 128 analog and a like number of digital signals, and prints output on a standard IBM "golfball" typewriter or teleprinter. A central concept of this scheme is that the computer be capable of providing shore-side engineers with sufficient information to carry out maintenance of the ship's machinery. The same computer with an expanded memory of 8192 words was installed in the stern freeze trawler ST. JASPER. It provided additional control functions including fault analysis and control action and trend recording. [15]

The same company that built the automation for GLEN AVON, GEC-Elliot, also provided the computer based automation-watchkeeping equipment for a total of 36 Brazilian operated cargo ships, the first of which was ITAQUICE. The installation performs automatic trend recording, alarm recording, indication of machinery malfunction, automatic logging of machinery and maneuvering recording.

In 1969, the Norwegian tanker TAIMYR was equipped with a computer from which other systems concerned with navigation, an autopilot, machinery monitoring and data logging have been developed. This system is notable in that it is modular in both its hardware and softward construction. Similar installations were later installed in the steam turbine tankers THORSHAVET and TABRIZ. [15A] In this same year, an IBM 1800 with 24K word memory was installed in the 10,000dwt M.V. ESQUILINO for data acquisition and processing concerning navigation and automation of machinery eventually envisaged.

A TOSBAC 3000 computer with 16K word memory supplemented by an 80K drum memory was installed in the 138,000dwt SEIKO MARU (also called the TOKO

MARU in some publications) which entered service in 1970. Features of this installation included:

(1) logging, monitoring and supervisory operation of main and auxiliary machinery.

(2) fault analysis and initiation of corrective action including engine speed reduction or shutdown and switching of machinery.

(3) limited health diagnosis of sick crew members.[16]

Four systems and a central computer developed jointly by Nippon Kokan Showa Shipping and the Oki Electric Company, Ltd., are being tested in the 261,000dwt tanker KINKO MARU. The system consists of an anti-collision subsystem, a ship's speed measuring subsystem, an automatic chart position plotter and a boiler monitor subsystem. The central computer is an OKITAC 4300 with 16K memory.[17]

Among the latest and most highly automated ships yet at sea are the standard 255,000dwt turbine tankers SEA SERPENT and SEA SWAN which are the first of a series. These ships are equipped with a computer system developed by Kockums of Sweden, probably the first instance that a shipbuilder as opposed to a subcontractor has been responsible for the design and supply of advanced electronic controls involving a computer. The Kockums 530 computer contains a general purpose digital computer manufactured by Kongsberg Vapenfabrikk of Norway and incorporated a 24K memory. The computer system features emphasize navigation and turbine control and include:

(1) a doppler log and satellite receiver for navigation

(2) automatic steering

(3) a Sperry autopilot

(4) automatic boiler regulation and combustion control

(5) automatic main engine control taking into consideration ship's loading and machinery thermal limits. [18]

The M.V. HOEGH MULTINA, a 52,000m^3 LPG carrier goes a step further than most. Not only does the system carry out a large number of functions concerned with engine monitoring and control, but a separate process computer analyzes the condition of machinery components and produces data for preventive maintenance as well as being available as backup for the main process mini-computer.

From the above, it can be seen that most of the development work in this field has been done in Europe, and some of the effort was government sponsored on a research basis. As of late 1971, there were slightly more than 20 ships at sea with digital computers installed for the performance of a variety of tasks. [19] Due to the relative scarcity of detailed technical information available, it is not clear how many utilize direct digital control.

3. Scope of the Project/Plan of Attack

It should be clear that the complete design of a direct digital control scheme (direct digital control is where the computer performs the control calculations) for a large bore diesel engine is a task of great magnitude requiring several men a number of months to accomplish. One estimate of typical software development costs for a program carrying out navigational and machinery applications is two to eight man years! In addition, under optimum conditions, there should be collaboration between the control engineer, the machinery designer and the naval architect. Therefore, the scope

of this project will be similar to a preliminary design effort, and further effort will be required to translate the control plan into reality.

The main plan of attack in accomplishing the task will be threefold:

(1) Simulation. In order to control a propulsion plant and avoid possible lengthy and costly experimental programs, one must be able to model the plant. Adequate models for large bore, low speed diesels have been developed by others (the work of E. R. Freeman is relied upon heavily in this paper), except that no models for the reversing of a direct drive low speed engine were found in the literature. Therefore, the first task was to develop such a model for the Burmeister and Wain (B/W) 7K98FF engine (also used by Freeman).

(2) Hardware Survey. If a control scheme were to be implemented, the designers must obviously be familiar with the hardware available for performance of the task; i.e., the hardware and software must complement each other. Therefore, a hardware survey covering sensors, signal processors/converters, mini process control computers, data display devices and actuators, was conducted by corresponding with leading manufacturers in the control field.

(3) Logic Design. In an effort to limit the design effort to an amount that could be feasibly accomplished by one individual, the logic design was carried out only to the flow diagram level. To do this, analyses of the functions to be performed, parameters to be measured, and the like had to be performed. The remaining work to be accomplished if the system were to be implemented included actual writing of the program for a specific installation and system testing (no small tasks indeed!). In addition to the above, a discussion of the problems associated with automation was included.

Since the main goal of this work is to construct the logic to effect the control of the diesel engine, the reader will see that the above is consistent with established computer control practice:

"...the control programmer should be familiar with the process to be controlled, the model and control strategy to be employed, the process instrumentation from which information is fed to the computer, and the computer system itself."[20]

CHAPTER I.

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CHAPTER II.

SIMULATION

1. General

As discussed previously, modeling and subsequent simulation is a very useful tool to the control engineer. In the diesel engine field, although there is not an overabundance of literature on the subject of propulsion plant simulation, the work of Freeman[1] is an excellent compilation of available material and is utilized extensively in the discussion that follows.

In many instances below, it is to be noted that either (1) different algorithms for certain parameters (e.g., shaft losses) could be used, or (2) optimization studies (e.g., propeller selection) or testing could be performed to further refine values used in the model, but this work was not considered to be a part of this project.

2. Low Speed Diesel Engine

2.1 Basic Relationships

The basic equations pertaining to diesel engines are found in several excellent references.[2,3]

The power produced in the engine cylinders, the indicated horsepower (IHP), is given by:

$$IHP = \frac{PLAN}{33000} \quad (HP)$$

where:

P = indicated mean effective pressure (lbs/in^2)

L = stroke (ft)

A = total piston area for a multi-cylinder engine (in^2)

N = revolutions per min (RPM) (two-stroke engine), or RPM/2 (four-stroke engine)

The available output shaft horsepower, brake horsepower (BHP) after losses due to friction and internal loads (attached pumps, turbochargers, etc.) is given by:

$$BHP = \frac{\eta_m PLA}{33000} \quad (HP)$$

where: η_m = the mechanical efficiency = $\frac{BHP}{IHP}$

The mean effective pressure, P, can be measured directly and is proportional to the energy released by combustion in the cylinder, which in turn is proportional to the amount of fuel injected per each power stroke. The amount of fuel injected per stroke is constant for a given fuel setting since a positive displacement pump mechanism is used on most diesel engines.

Rotational power is expressed as the product of torque, τ, and rotational speed, ω, and is equal to BHP:

$$\frac{\eta_m PLAN}{33000} = \tau\omega = \tau 2\pi N$$

Therefore:

$$\tau = \frac{\eta_m PLA}{(2\pi)33000}$$

or torque is constant for a given fuel setting regardless of the rpm. The above relationships are known as the ideal torque-rpm and power-rpm relationships.

2.2 Assumptions

(1) Although Freeman discussed other models, the preceding was used

in his simulations, and also in the reversing simulation that follows. It is to be noted that the model does not produce the oscillatory torque characteristic of internal combustion engines, but that was not considered necessary for these studies.

(2) References (4) and (5) were initially used to estimate the moment of inertia of the engine for use in the dynamic equations, and later refined by reference (12).

(3) Because Freeman used the Burmeister and Wain 7K98FF, for matters of consistency and expediency the same engine was used in the reversing model described here. From the test stand data it was found that for the 7K98FF, torque-fuel settings were not quite linear and therefore were stored in the computer (see Appendix B).

2.3 Reversing

Reversing a low-speed engine is accomplished by the following procedure:[6,7]

(1) Fuel setting is positioned to zero;

(2) The starting air and fuel mechanisms (also the exhaust valves in the case of a uniflow scavenged engine like the K98FF) are set to the "astern" position;

(3) If necessary, the ship's speed is allowed to decrease until the "reversing speed" is reached. (Reversing speed is defined as that speed at which the torque that can be developed by admitting starting air to the engine in the reverse direction is sufficient to stop the engine and propeller and reverse same.)

(4) Cut in starting air;

(5) When the engine has achieved firing speed in the reverse direction, the fuel setting is advanced to the appropriate position and application

of air is terminated.

In the reversing model the following parametric values were used:

Initial ship's speed:	12 knots
Time for fuel setting to reach "no fuel" position:	.3 sec.
Time to shift cams for running in astern direction:	2-3 sec.
RPM at which reversing air cut:	52
Reversing torque developed by the application of air to the engine (4 cylinders):	1.090×10^6 ft.lbs.
Firing speed:	.15 rev./sec.
Time for fuel setting to go from "no fuel" to "full fuel" setting:	approx. 4 sec.

3. Propeller

The model used to simulate the fixed-pitch propeller was that proposed by Van Lammeren, Van Manen and Oosterveld for the Wageningen B. Series.[8] In this model, the non-dimensionalized thrust and torque coefficients are represented in the form of a Fourier series as a function of hydrodynamic pitch angle β, defined by:

$$= \arctan \frac{(\ V_A\ )}{.7\ ND}$$

where:
V_A = propeller speed of advance (ft.sec.)
N = propeller rotational speed (rev./sec.)
D = propeller diameter (ft.)

The non-dimensionalized thrust and torque coefficients, C_T^* and C_Q^*, are given by:

$$C_T^* = \sum_{K=0}^{K=M} A(K)\cos(K\beta) + B(K)\sin(K\beta)$$

$$10C_Q^* = \sum_{K=0}^{K=M} C(K)\cos(K\beta) + D(K)\sin(K\beta)$$

The thrust (T) and torque (Q) are then found by using the relationships:

$$T = C_T^* \left\{ \tfrac{1}{2}\rho [V_A^2 + (0.7\pi ND)^2] \tfrac{\pi}{4} D^2 \right\} \text{ (lb)}$$

$$Q = C_Q^* \left\{ \tfrac{1}{2}\rho [V_A^2 + (0.7\pi ND)^2] \tfrac{\pi}{4} D^3 \right\} \text{ (ft-lb)}$$

Reference (8) shows that the values of the coefficients A(K), B(K), C(K), and D(K) as calculated by a 10-term series very closely approximate the measured characteristics of the B Series. As in the work of Freeman, the B 4-70 screw (but with a 23-foot diameter) was used in the reversing model, although coefficients are also presented for others in the series in the reference.

As will be shown later, the propeller moment of inertia must be calculated for use in the dynamics equations. The moment of inertia of the propeller was estimated using references (9) and (12) with an allowance of 25% of the inertia for added mass.[10]

4. Shafting

As in the work of Freeman and others, shaft friction losses are represented in a "table-look-up" form in the simulation. Information from Burmeister and Wain indicated that these losses accounted for about 10% of rated torque at design load, and thus the shaft friction torque, Q_f, was approximated by the expression:

$$\begin{aligned} Q_f &= 25000 \text{ (ft-lbs)} \quad 0 \le N \le .417 \\ &= 60000\, N \text{ (ft-lbs)} \quad N > .417 \end{aligned}$$

where: N = shaft speed (rev/sec)

5. Ship Characteristics

To model the ship, a number of characteristics familiar to the marine engineer must be considered.

5.1 Wake Fraction and Thrust Deduction Factor

The wake fraction, w, determines the velocity at which the propeller is advancing in relation to the ship velocity, i.e.,

$$V_A = (1-w)V$$

where: V_A = propeller speed of advance

V = ship speed

w = wake fraction

The thrust deduction factor, t, indicates how much propeller thrust is reduced due to hull interaction:

$$T_1 = T_{OW}(1-t)$$

T_1 = net thrust

where: T_{OW} = open water propeller thrust

t = thrust deduction factor

Freeman provides a discussion of the manner in which these two parameters have been treated in previous simulation efforts, and in research work to determine their variation under different ship's speeds and shaft rpm conditions. He concludes "...it can be seen that there is no general agreement on the treatment of these two factors. The feeling appears to be that these two factors are so small that any errors in their treatment will have negligible effects on the total simulation."[11] Although this may not always be true, and w and t do vary, this author assumed constant values of wake fraction ($w = 0.04$) and thrust deduction factor ($t = 0.02$), as did Freeman.

5.2 Added Mass

As in the case of other characteristics, the manner of treatment of added mass by various authors has not been universal. Model testing and other techniques might yield a better number, but a value of 10% has been used here and in Freeman's work.

5.3 Resistance/Displacement

It is clear to the marine engineer that for the most accurate representation of resistance, the modeler should use data from actual towing tank tests, standard series data, or other sources. Since a hypothetical ship was involved in the reversing model, the expressing for resistance (R):

$$R = 611.8 \quad V^2$$

where: V = ship velocity (ft/sec)

was used. This loosely follows from (1) application of the "Propeller Law" that resistance is proportional to the square of velocity for ships where the wave drag is small, and (2) equating propeller thrust and approximate design speed (assumed to be 15-16 kts.) for a 90,000-ton displacement ship driven by a 24,500 bhp engine.

6. Ship Dynamics

The ship propulsion equations (with no external forces or rudder movement) are first order, non-linear differential equations:

Thrust

$$\frac{MdV}{dt} = T - R$$

where: M = mass of ship $\left(\frac{\text{lb-sec}^2}{\text{ft}}\right)$

V = ship velocity (ft/sec)

T = thrust (lbs)

R = resistance (lbs)

Torque

$$I \frac{dN}{dt} = Q_D - Q_F - Q_P$$

where:

I = rotational inertia of drive train (lb-ft-sec^2)

N = propeller speed (rev/sec)

Q_D = prime mover drive torque (ft-lb)

Q_F = shaft friction torque (ft-lbs)

Q_P = propeller torque (ft-lbs)

The two equations are coupled through the propeller terms T and Q_P. Solutions of the equations were obtained using the Dynamic System Simulation Program (DYSYS) on the M.I.T. joint Civil Engineering/Mechanical Engineering Interdata 70 computer. The solution employs a fourth order Runge-Kutta integration technique.

7. Results

Using the model described above, a simulation of a "crash-back" maneuver from an initial speed of 12 knots was performed. Figures 2-1 and 2-2 are plots of:

shaft speed
ship speed
distance travelled
propeller torque
diesel torque
thrust

from the simulation. The actual computer program utilized in the simulation is presented in Appendix B.

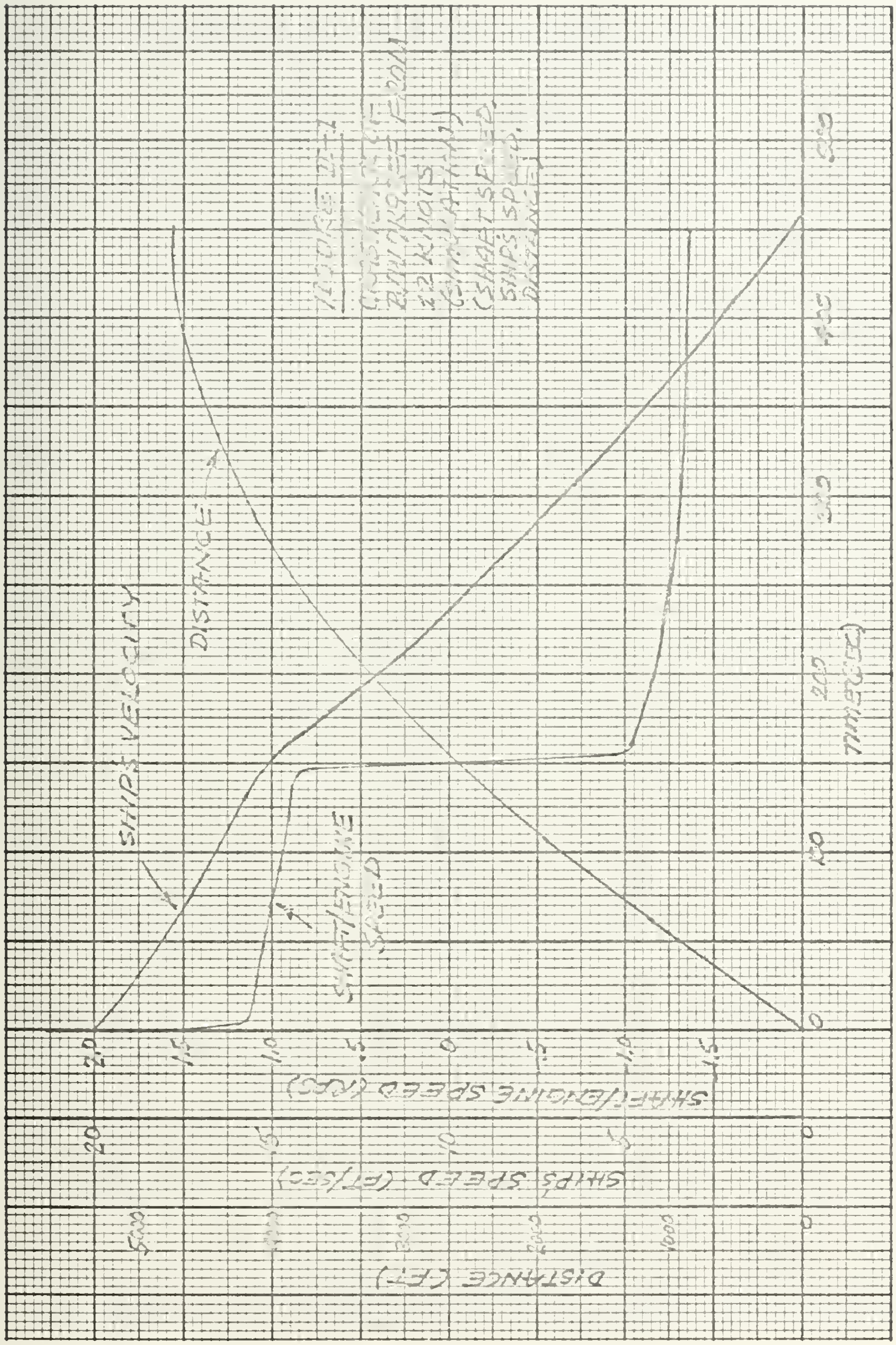
SHIPS VELOCITY
DISTANCE
SHAFT/ENGINE SPEED
FIGURE II-1
22 KNOTS
(SIMULATION)
(SHAFT SPEED,
SHIPS SPEED,
DISTANCE)
2.0
1.5
1.0
.5
0
-.5
-1.0
-1.5
SHAFT/ENGINE SPEED (RPS)
20
15
10
5
0
SHIPS SPEED (FT/SEC)
5000
4000
3000
2000
1000
0
DISTANCE (FT)
0
100
200
300
400
500
TIME (SEC)

Figure II-1

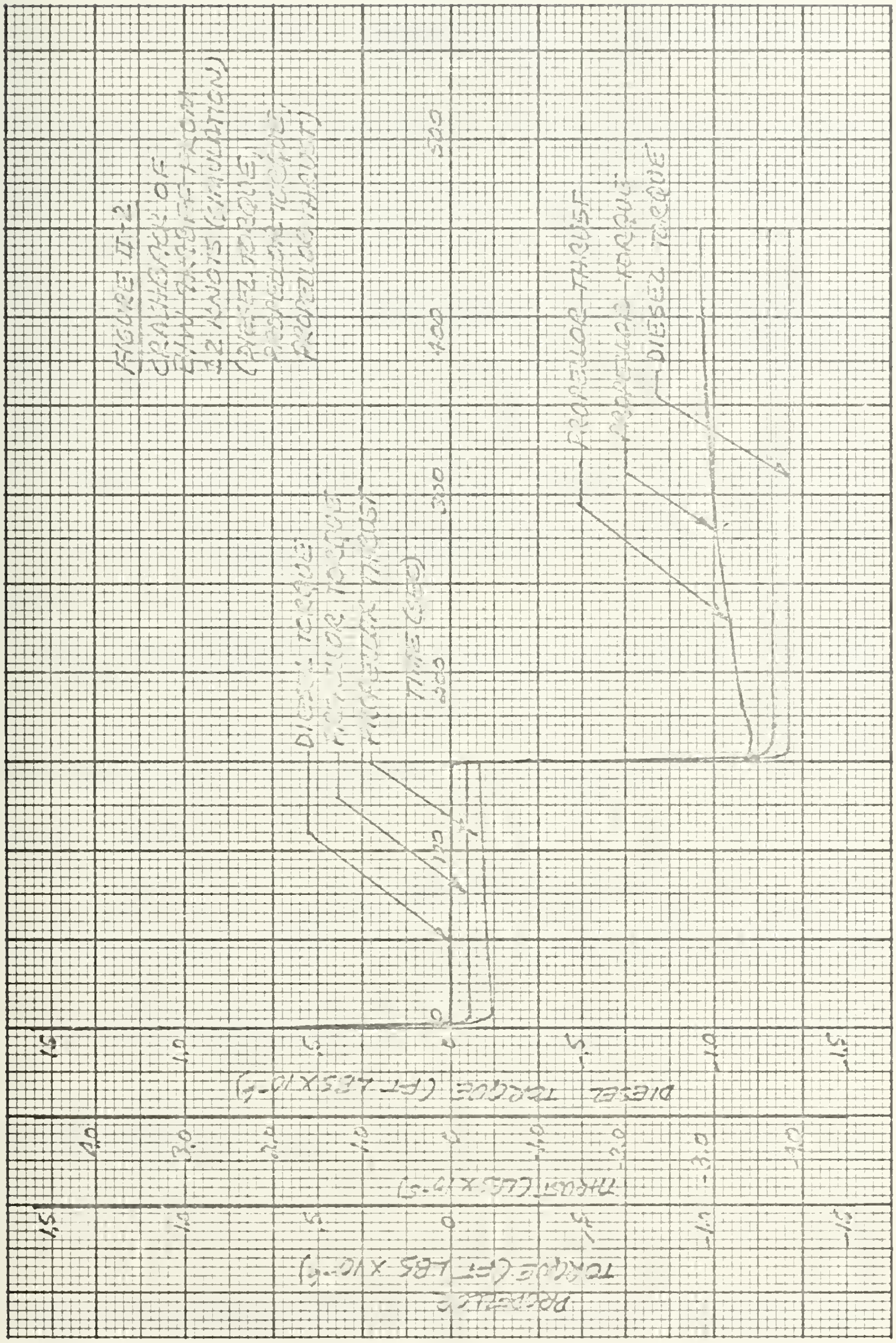
FIGURE II-2
GRAPHICAL OF
32 KNOTS (SIMULATION)
(DIESEL TORQUE)
PROPELLER TORQUE
PROPELLER THRUST
DIESEL TORQUE
PROPELLER TORQUE
PROPELLER THRUST
TIME (SEC)
0
100
200
300
400
500
DIESEL TORQUE (FT-LBS X10⁻⁴)
THRUST (LBS X 10⁻⁵)
PROPELLER TORQUE (FT-LBS X10⁻⁴)
1.5
1.0
.5
0
-.5
-1.0
-1.5
4.0
3.0
2.0
1.0
-1.0
-2.0
-3.0
-4.0

Figure II-2

CHAPTER II.

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CHAPTER III.

DIGITAL CONTROL TECHNICAL DESIGN CONSIDERATIONS

1. General

Having reviewed some examples of ships having digital computer control applications, and presented an analytical model for the low speed, direct drive diesel engine/fixed-pitch propeller combination, the considerations upon which the design of a digital control scheme depends are next investigated. It is upon this foundation that the validity and feasibility of the remaining work rests. Each of these considerations, within the scope of this project, will be addressed in Chapter V. It should be realized that although many of the items to be discussed are interdependent, they will be presented individually, and that much of the material is drawn from general process control theory/practice, there being little published information concerning details and considerations of shipboard computer installations. The following is not claimed to be an exhaustive list, but only representative of technical areas to be considered in the design of a digital computer control system. Other non-technical areas will be briefly discussed in Chapter VI.

2. Control Strategy/Functions to be Performed

2.1 The Basic Scheme

As in any systems analysis related work, before significant work can be accomplished, the overall goals, i.e., the control strategy, must be decided upon. Although in this particular case, direct digital control (DDC) has been selected as the control scheme, there are many others possible. They are usually classified according to the degree of direct inclusion of the

computer in the control loop;[1] besides DDC, alternatives include (see Table III-1 for definition of terms):

(a) Process monitoring with data reduction

(b) "Off line" and "open loop" control

(c) "On line" but "open loop" control (or "operator guide" control)

(d) "On line" and either "open" or "closed loop" steady state supervision of plant control according to external criteria

(e) "Closed loop," "on line" steady state control

(f) "Dynamic" control

The questions that must be answered before the selection of the basic control scheme is made include: (1) What is to be the role of the operator in the control scheme? (2) How rapid a response time is required? (3) How many parameters need to be monitored/controlled? (4) What is the reliability of each alternative? (5) What is the cost? It is obvious that if unattended machinery spaces are desired, the degree of inclusion of the computer in the control process must be high.

2.2 Functions to be Performed [2]

Computer functions in process control may be divided into two categories, supervisory functions and control functions. In its supervisory role, the computer assists or guides the operator in making his control decisions (which may be of an operational or maintenance nature) by presenting him with accurate and timely information. In its control function, the computer explicitly calculates control action to be taken and either advises the operator to that effect (open loop) or imposes control automatically in the closed loop mode.

Table III-1

DEFINITION OF TERMS

Off-line control--the computer receives information through a non-machine (human) intermediary.

On-line control--the computer is directly and continuously connected to the process.

Open loop control--uses the computer to calculate control action, but has no direct connection to the process; i.e., the operator must carry out required action.

Closed loop control--control actions calculated and recommended by the computer are directly applied to the process.

Direct digital control--the computer acts like a conventional controller, and its signal goes to the final control element, such as a valve actuator.

Dynamic control--process control during transients as well as steady state.

2.2.1 Process Supervision--Monitoring

Regardless of the sophistication of the eventual control system, the necessary starting point for the computer is to determine the current conditions in the process including the status of instruments, process variables, and equipment. In accomplishing this, many or all of the following may be carried out:

(a) Sensing instruments are scanned either on a fixed time schedule, on operator demand or program/process demand.

(b) The sensed "signal" is processed, and checked for instrument or other error.

(c) Signals are analyzed for trends.

(d) The status of equipment is determined; "forbidden" combinations of equipment can be prevented.

(e) Several sensing instruments can be analyzed as a group to determine a particular machinery performance.

(f) Leakage rates can be determined by analyzing level changes.

2.2.2 Process Supervision--Logging and Alarming

The signal from the instrumentation is the medium whereby the computer is updated about the process. Whether DDC is used or not, certain of this information must be made available to the operator even in an unattended machinery installation for such requirements as: (1) follow-up corrective action after equipment or other malfunction,(2) preventive maintenance, and (3) plant status at the ship control and power plant control stations and elsewhere.

The computer is capable of maintaining complete logs, thereby freeing an

operator from this chore. When necessary, current or previous information may be presented on a variety of output devices for analysis, and operator attention may be called by several means. Logging is usually done periodically, with demand option.

2.2.3 Process Control--Preplanned Control

Fixed or predetermined control action can be carried out by the computer; great care must be taken to ensure that it is valid over the anticipated range of plant conditions. Preplanned control can be applied either as a standard operating practice or in the form of sequential actions.

Standard operating practice may be used when it is desired to repeat relatively simple evolutions such as maneuvering (speed changing) and the like, where a certain response is expected, or in casualty situations where immediate corrective action is necessary regardless of other plant conditions.

Sequencing control may be used whenever a series of predetermined control actions needs to be carried out, and considerable monitoring and logical checking are necessary before proceeding in the sequence. Typical of these applications is plant (main or auxiliary) startup and shutdown, or follow-up corrective action after immediate action (by standard operating procedure) has been carried out in a casualty situation.

2.2.4 Process Control--Regulatory Control

This application is the familiar situation where computer control is applied to maintain process variables at desired values. A variety of control concepts may be utilized including feedback, feedforward and multivariable control (control of many variables on an integrated basis taking into account

the complexities of their interrelationships vice simple cascading control).

2.2.5 Process Control--Optimizing Control

This application is usually the most complex, most expensive, and frequently the most financially rewarding long-run application of computer control. It is here that the overall economic implications of the control action are explicitly and deliberately taken into account. Unfortunately, optimizing control is not appropriate in all control situations, but when it can be used, the ability of the computer to combine the consideration of current variables with physical and economic laws and criterion can be a most powerful tool.

Thus, from almost the outset of the control design effort, the overall goals and scope of the eventual system must be clear in the designer's mind. It may be possible to perform certain evolutions such as cold plant startup and shutdown in port manually or this may be performed under computer control; regardless of the alternative chosen, the impact on the complexity, size and cost of the control system are obvious.

3. Parameters to be Measured/Sensors

The exact parameters to be measured and the frequency of their measurement will depend on the engine installation to be controlled and the extent of control to be utilized. A summary of the fundamental measurements to be taken on a typical plant might include: [3]

a. temperature

b. pressure

c. level

d. flow

e. speed (rotational & linear)

TABLE III-2[4]

VARIABLE	TYPE OF SENSOR	SIGNAL CHARACTERISTICS	FILTERING REQUIRED *	TYPICAL CONVERSION TECHNIQUES	REMARKS
Temperature	Thermocouple	Low Level, <40 m.v.; Low impedance <100 ohms	NO	DC directly to input. Known reference temp. required.	Low level is disadvantage. Requires cold reference.
	RTD - DC excited	Medium Level, 100-500 m.v.; may not be at ground; higher impedance >100 ohms	Minor, depends upon excitation and cabling	DC directly to input	Requires accurate excitation voltage and bridge. Three leads usually.
	RTD - AC excited	" " " "	Function of AC/DC Converter Filtering	AC to DC Converter required	Phase shift is a problem
	Recording instrument	Obtained from follow-up slide wire	Minor, depends upon excitation	DC directly to input	Slide wire excitation and means of checking by computer must be provided.
	Millivolt to current transducer	See Pressure P-I Transducers			Occasionally used in duplex systems with both conventional and digital instrumentation.
	Vapor bulb	See Pressure P-I Transducers			
Pressure	Strain gauge	Low Level dc or ac; Low impedance	Function of AC/DC Converter Filtering	If AC an AC to DC converter required	Requires accurate excitation voltage and bridge. Phase shift is a problem with ac excitation

*Required in addition to normal input filtering with at least a 10 to 1 rejection at 60 cps. Good cabling practice is assumed.

TABLE III-2 (Cont'd.)

VARIABLE	TYPE OF SENSOR	SIGNAL CHARACTERISTICS	FILTERING REQUIRED *	TYPICAL CONVERSION TECHNIQUES	REMARKS
Pressure	P-V transducer DC voltage	High level voltage; signal typically 1-9 v., 0-5 v., 0-25 v., etc., may be rather high impedance	Required on some transducer types	None, provided input channel has several ranges.	Sensor usually direct acting, "open loop" type.
	P-I transducer DC current	Current signal; 5:1 range; offset zero; typically: 1-5 m.a., 4-20 m.a., 10-50 m.a., etc.	Required on some transducers where ripple can be as high as 10%.	Resistance shunt at computer.	Low impedance generally noise insensitive. Principle of sensor operation can be either force balance or "open loop" direct action.
	P-I transducer AC voltage	Voltage amplitude, typically 0-.2, 0-.5v.	Function of AC/DC converter	Special AC to DC converter; stringent requirements on impedance and phase	Difficult phasing problem. AC to DC converters available from AC instrument manufacturer.
Flow	Orifice-differential pressure	See Pressure Measuring Techniques			Computer correction for density, temperature, flow coefficient, requires measurement of these variables also.
	Turbine	Pulse rate indicates flow rate	High frequency filter only.	Normally accepted as a digital input. External pulse accumulation may be used.	Example of where analog quantity (flow) is directly converted to digital quantity (pulse) by sensor.

TABLE III-2 (Cont'd.)

VARIABLE	TYPE OF SENSOR	SIGNAL CHARACTERISTICS	FILTERING REQUIRED *	TYPICAL CONVERSION TECHNIQUES	RAMARKS
Flow	Mass flow	Pulse rate indicates flow rate	High frequency filter only.	Normally accepted as a digital input. External pulse accumulation may be used.	Example of where analog quantity (flow) is directly converted to digital quantity (pulse) by sensor.
	Magnetic	Moderate voltage or current signal.	May be required.		Conductive fluid required, signal varies with conductivity.
Composition	X-ray emission gauge	d.c. voltage, typically 10 v.	Yes, high hash content.	d.c. voltage direct to input.	Control of calibration is preferably under computer control.
	Gas chromatograph	dc voltage from slidewires of electromechanical peak-picker or from electronic "peak-pickers"	Minor, depends upon excitation for slide wire or nature of electronic circuit.	DC direct to input, Peak holding circuits required.	In batch process control, contacts necessary to acknowledge availability of new set of readings; if used on more than one stream sample control contacts necessary and/or channel identification.
Voltage-AC	Potential transformer and thermal converter	DC millivolt range, low impedance	Not usually	DC direct to input	True rms measurement, but between ac input and dc output is nonlinear. (Square law).

TABLE III-2 (Cont'd.)

VARIABLE	TYPE OF SENSOR	SIGNAL CHARACTERISTICS	FILTERING REQUIRED*	TYPICAL CONVERSION TECHNIQUES	REMARKS
Voltage-AC	PT & peak rectifier & filter	dc volt range impedance function of filter	Usually considered to be part of converter.	DC direct to input	Waveform sensitive. Slow response due to filters.
	PT & averaging rectifier & filter	" " " "	" "	" " "	Less waveform sensitivity. Slow response due to filters.
Current-AC	Current transformer & thermal converter	" " " "	" "	" " "	Same as corresponding section AC voltage.
	CT & peak rectifier & filter	" " " "	" "	" " "	" " "
	CT & average rectifier & filter	" " " "	" "	" " "	" " "
Voltage-DC		May be from microvolts to kilovolts; may be floating, balanced or unbalanced with respect to ground.	Possibly extensive depending upon source voltage	Special preamps with low level; special resistive attenuators with medium and high level signals.	Slow response if extremely sensitive preamps. Power dissipation and accuracy may be problems on special attenuators.

TABLE III-2 (Cont'd.)

VARIABLE	TYPE OF SENSOR	SIGNAL CHARACTERISTICS	FILTERING REQUIRED*	TYPICAL CONVERSION TECHNIQUES	REMARKS
Voltage-DC	DC-potential transformer or transductor.	Moderate level current, full wave rectified.	Usually extensive	Resistance shunt & filter.	Provides isolation from ground detector circuitry & large induced switching transients.
Currents-DC	Shunt	Up to 100 mv full scale, floating with respect to ground or artificially elevated by ground detector circuitry.	Extensive, depends on nature of signal.	DC direct to input	High common mode voltages from accidental grounds or ground detector circuitry are a problem.
	DC-Current Transformer	Moderate level current, full wave rectified.	Usually extensive	Resistance shunt and filter.	Provides isolation from ground detector circuitry & other high common mode sources.
Power-AC or vars	Thermal Converter	Millivolts dc, low impedance	No	DC direct to input	Phase shift transformer required for vars.
Speed	Tachometer DC	DC voltage 0 to 50-250 volts, low impedance, several percent commutator ripple	Usually to reduce commutator ripple.	DC direct to input if flexible input system.	Linearity usually affected by loading.
	Tachometer AC	AC voltage amplitude 0-50, 0-100 volts, low impedance also can use frequency as analog.	Extensive in AC to DC conversion	AC to DC converters If frequency, external accumulators required and handled as digital signal.	Same comments as other AC/DC converters. Example of where analog quantity is directly converted to digital quantity by sensor.

Table III-3

CONTROL PARAMETERS MEASURED IN TYPICAL LOW SPEED DIESEL INSTALLATION [5]

Main engine cooling system
Pump suction and delivery pressures
Cooler inlet and outlet temperatures
Cooling water tank level gage
Reserve cooling water tank level gage
Outlet temperature of each component cooled

Main engine lubricating oil
Pump suction and delivery pressures
Cooler inlet and outlet temperatures
Sump tank level gauge
Pressures to and from filters
Pressure at turbochargers
Temperature at each main bearing
Pressure at main bearing inlet mainfold
Cylinder lubricating oil pressure
Temperature of propeller shaft bearings
Pressure of oil to reduction gears
Temperature of reduction gear bearings
Temperature of thrust bearing

Main engine exhaust gas
Temperature of gas leaving cylinder
Temperature of gas to and from blowers

Main engine pressure charging system
Temperature of air at inlet
Air pressure leaving filters
Temperature of air leaving blowers
Temperature of air leaving coolers
Turbocharger speed
Temperature inside scavenge belt

Main engine fuel oil
Oil pressure to and from high-pressure fuel pumps
Oil pressure to and from heaters

Main engine starting air
Pressure in each air bottle
Pressure in starting manifold on engine

f. torque

g. gas analysis

h. valve position/equipment running

i. viscosity

$$\left.\begin{array}{ll}\text{j.} & \text{salinity}\\ \text{k.} & \text{voltage}\\ \text{l.} & \text{current}\\ \text{m.} & \text{kva, kvar, kw}\end{array}\right\}\ \text{auxiliary plant only}$$

Mostof the sensors used in practice for measuring parameters are analog, although some digital transducers are available. A summary of plant instrument sensors which may be used is contained in Table III-2. Selection of actual hardware may depend on many things including economics, installed engine instrumentation, size and accuracy of the sensor/transducer, and response time necessary. A typical list of parameters measured for a slow speed diesel installation is shown in Table III-3.

4. Signal Processing and Transmission

4.1 Input

Typical basic elements in connecting a process with a computer are shown in Figure III-1. The components that make up the so-called "front end" of the information gathering system are necessary to transmit the signal to the computer, modify the transducer output in terms of magnitude and impedance to conform to the computer input requirements, remove undesirable frequencies and noise by filtering, and convert the signal to a form acceptable to the computer. This task is greatly simplified by "multiplexing" which is simply the random or sequential switching of many matched and filtered transducer

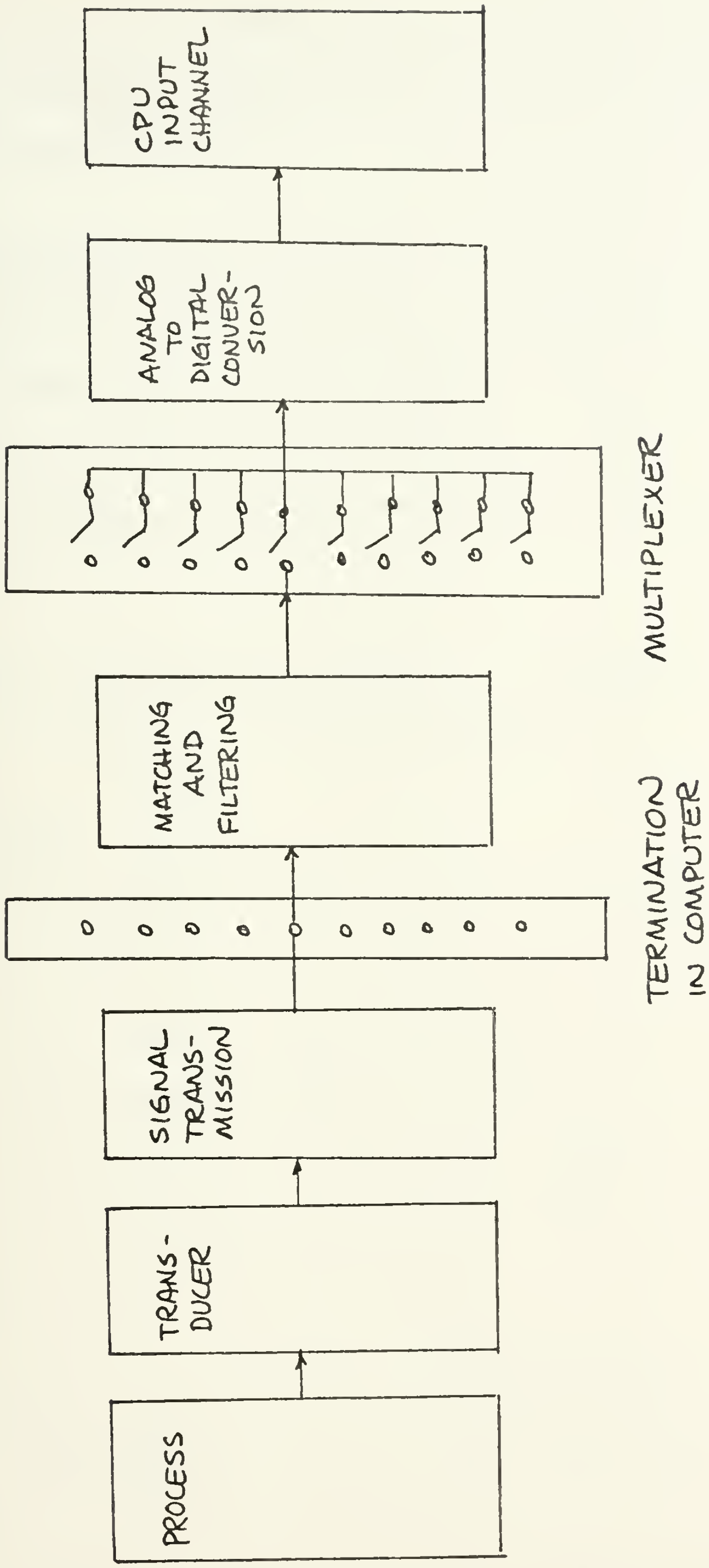

FIGURE III-1

ADAPTING A PROCESS MEASUREMENT (ANALOG) FOR INPUT TO A CONTROL COMPUTER

outputs into one common conversion device. Multiplexing can take place in the digital realm, the analog realm, or in the conversion process (analog to digital or vice versa).

Not all information from the process is in analog form. Besides a few digital sensors (i.e., temperature, etc.) there are simple switches or on-off devices which indicate process status, alarm conditions, valve positions, equipment status and the like which are digital in nature. The basic digital input channel is similar to Figure III-1 except for the absence of the converter.

Various types of A/D and D/A converters are discussed in many texts, including criteria to be used in choosing among them.

4.2 Output

In many ways, the output channel (i.e., to the process) resembles the input channel (see Figure III-2). To control process functions, the information developed by the computer program must be put into a form that is compatible with the terminal equipment which is to receive this information. Unless these terminal devices can utilize digital signals, digital to analog conversion (D/A) is necessary, and often an output multiplexer is used in signal transmission.

In the selection of converters, it is essential that the designer know how accurate the presentation is (i.e., output versus input), and the speed of conversion.

5. The Central Processing Unit and Related Subjects [7]

The central processing unit (CPU) is the device that through the programs

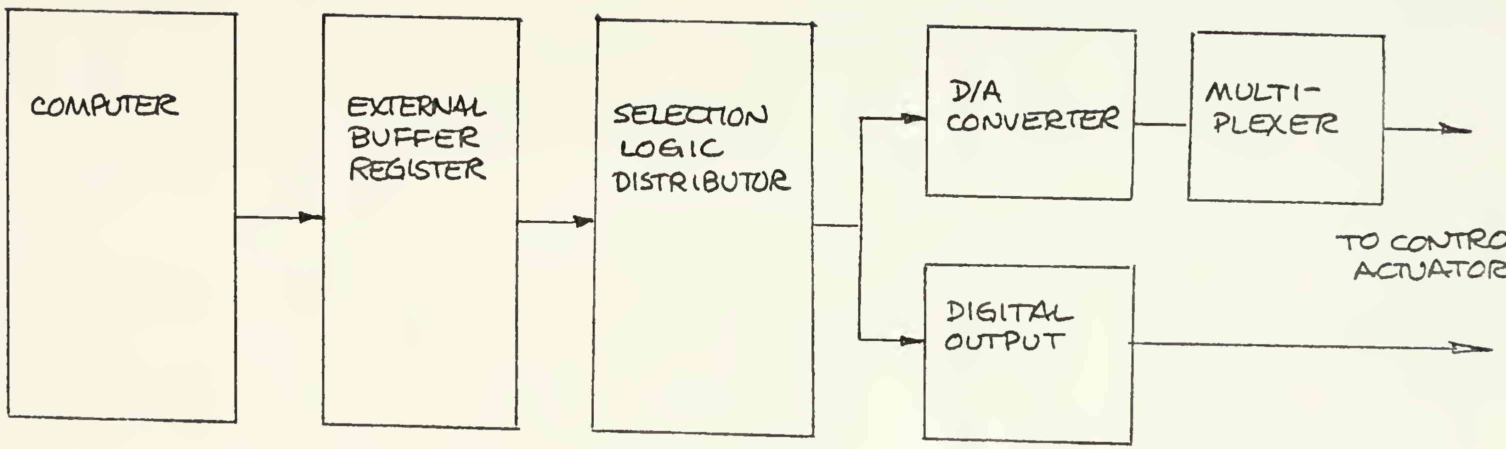

FIGURE III-2

TYPICAL OUTPUT CHANNEL

stored internally in working storage, directs the operational procedures of the entire system. Important features of CPU design include word size, instruction set and addressing methods, information transfer, and priority interrupt. Together, these influence programming, effective computing speed, and storage utilization. In the control of a marine propulsion plant, the system requirements will, in all probability, allow a "mini-computer" to be utilized.

Word size and structure of words must be such as to ensure adequate precision in calculations and to allow direct addressing of any storage location within one instruction word.

Instructions in the form of command lists of process control computers are designed to facilitate process programming. Desirable features include: (1) commands to transfer variable length blocks of data between storage units or locations within storage, (2) single commands which carry out more than one operation, (3) flexible addressing modes for direct and immediate addressing, (4) address modification by use of index registers. These features reduce the number of"housekeeping" instructions, thereby benefiting the system by saving storage and increasing processing speed.

Information transfer strongly influences the capabilities of the overall control computer system. The computer should be capable of simultaneous or parallel transfer. Three possible transfer methods are:

(1) Program entry: every piece of information into or out of the processor's storage proceeds under direct control of program commands; input and output cannot proceed simultaneously or be overlapped with computations; use of this method hampers on-line, real time capability.

(2) Direct entry: the input or output device uses a stored read or

write cycle without otherwise affecting the CPU; this unburdens the processor, allowing simultaneous input/output functions and computation. The principal disadvantage is the requirement for external control circuitry and switching.

Priority interrupt is a design characteristic of the processor that gives it the ability to suspend work on a program in progress upon receipt of an interrupt signal, branch to another program in response to this signal, perform some specified routine, and then return to the original program. This capability gives the processor a highly efficient means of reacting to emergency conditions in the plant. Interrupt lines into the computer are activated by switches, electronic impulses, or other means that can be internally or externally initiated. Through a combination of hardware and programming, an interrupt priority system may be established (i.e., the computer will respond to a low lube oil pressure condition even though a fresh water jacket outlet temperature may be slightly above the alarm point).

Priority interrupt also greatly simplifies real-time programming by allowing greater independence of various routines. It allows complicated program interleaving of independent routines, while alleviating the burden from the master program for housekeeping. In fact, program organization may be the prime justification for an interrupt system.[8] In constructing the interrupt features, the designer must have a detailed knowledge of the physical plant/process dynamics before assigning priorities.

6. Other Input/Output (I/O) Devices

Besides the signals to and from the process (process I/O), there are two other I/O categories of concern to the system designer, operator I/O and

computer I/O.[9] (See Figure III-3.) The operator's channel or console which would be on the bridge and/or in the control room, provides the translation and communication links between the operator(s) and the propulsion plant. The computer I/O channel is the basic program loading channel, the output channel for machine readable information, and the communication link to programmers and service engineering people for diagnostic input/output.

A growing trend in computer design is to incorporate within the I/O channels the basic logic and certain control functions to unburden the CPU, for example, comparing a measurement with a standard value to detect out-of-limit inputs. Such features as the above, combined with buffer registers and other techniques simplify programming and greatly improve the capability of the control computer system.

Modularity of the I/O sections is common in practice, for the control computer must be flexible enough to be utilized economically in a wide variety of applications and environments.(In particular, one must be extremely careful that all components of the shipboard system can perform satisfactorily in the at sea propulsion plant environment.) For this reason, control computer systems offer input and output selection capabilities which are easily expandable in small increments to more than 2000 analog and digital inputs, several hundred analog and digital outputs, and multiple logging and display devices.

I/O devices from which the system designer may choose include:

(1) typewriters

(2) teleprinters (teletypes)

(3) line printers

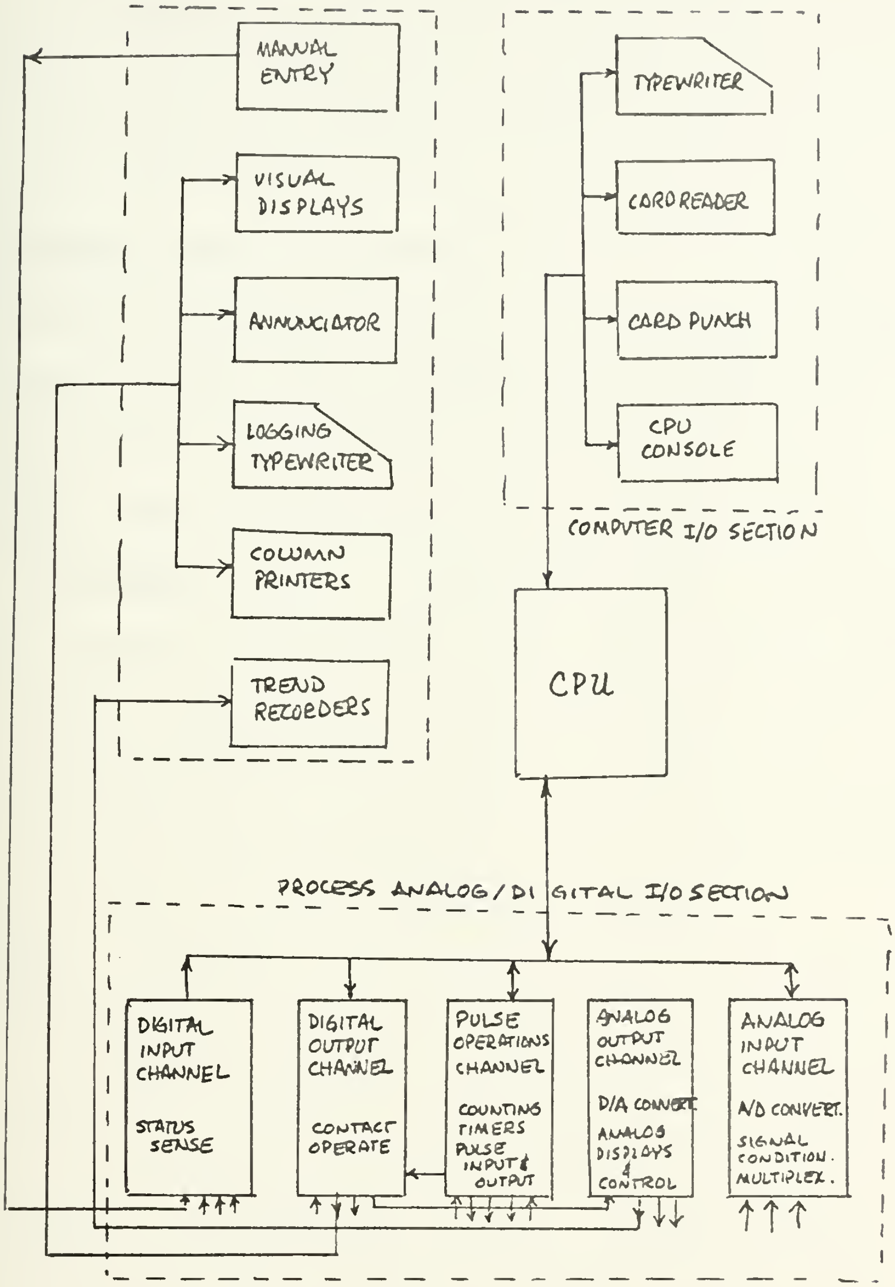

FIGURE III-3

INPUT & OUTPUT SECTIONS OF A CONTROL COMPUTER

(4) graphic display recording instruments/consoles

(5) digital and analog audio/visual displays

(6) card/tape readers and punches

(7) manual entry devices

7. Final Process Elements: Actuators[11]

The last physical element to be considered is the actuator through which computer control is implemented. Although digital control may favor electrical actuators, there are three categories of actuators from which to choose:

Hydraulic: may be single or double acting; linear or rotary motion obtainable. Advantages include: (1) high efficiency at full power and speed; (2) smooth, stepless, positive motion over a great velocity range; (3) extremely high output power and velocity for given size and weight; (4) fast acting; (5) can be designed to fail 'as is' on loss of power. Disadvantages include: (1) need for separate hydraulic system; (2) high pressure oil implies fire hazard if have a component containment failure.

Pneumatic: widely used where speed of response not a vital factor; can be similar in design to hydraulic, but also has a diaphragm feature. Advantages include: (1) inexpensive; (2) no fire hazard; (3) operators generally familiar with pneumatics since widely used; (4) stored air can be used on loss of compressor. Disadvantages include: (1) needs separate air supply; (2) relatively slow acting; (3) low efficiency; (4) needs relatively complicated locking device to be held in place on loss of air supply.

Electric: when used with a computer, eliminates need for an electric/hydraulic or electric/pneumatic converter; motion can be linear or rotary; three phase ac motors most commonly used. Advantages include: (1) no external system needed; (2) high efficiency; (3) clean. Disadvantages: (1) not

suitable for use in explosive atmospheres; (2) low power/weight ratio; (3) maintenance relatively complicated.

Selection of actuators for a specific application must clearly be governed by the technical aspects of the plant or by economic requirements or both. Factors influencing the choice include:

Technical	Environmental	Life	Cost
Use: remote, manual or automatic	Atmosphere	Short	Limited
Rotary or linear motion	Shock	Medium	"No limit"
Speed of response	Vibration	Long	
Load to be handled	Temperature (ambient)		
Positioning accuracy			
Distance from controller			
Size/power ratio			
Weight			
Efficiency			

8. Back-up Control/Reliability [12]

Although it is not within the scope of this paper to analyze in detail specific system reliability, the designer cannot ignore the fact that failures will eventually occur to some components in the control system.

In discussing reliability, one must first define what constitutes failure in the sense of loss of control. Loss of an individual input or output line

is to be expected more frequently than failure due to the CPU. Because individual channel failures may not cause system shutdown, the maximum number which may be out of service at any one time will have to be established.

In those instances where the control system is partially or completely inoperable, backup means must be available. Possibilities include:

(1) Manual control devices inherent in the plant equipment, e.g., locally mounted indicators or hand-operated valves, etc.

(2) Simplified manual controls to be operated from the central control room with independent (from the computer system) instrumentation for the operator.

(3) Complete and independent analog control loops.

(4) Redundancy in the digital system.

Each of these alternatives has its drawbacks, most notably the latter two which involve considerable equipment and expense.

CHAPTER III.

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CHAPTER IV.

HARDWARE

1. General

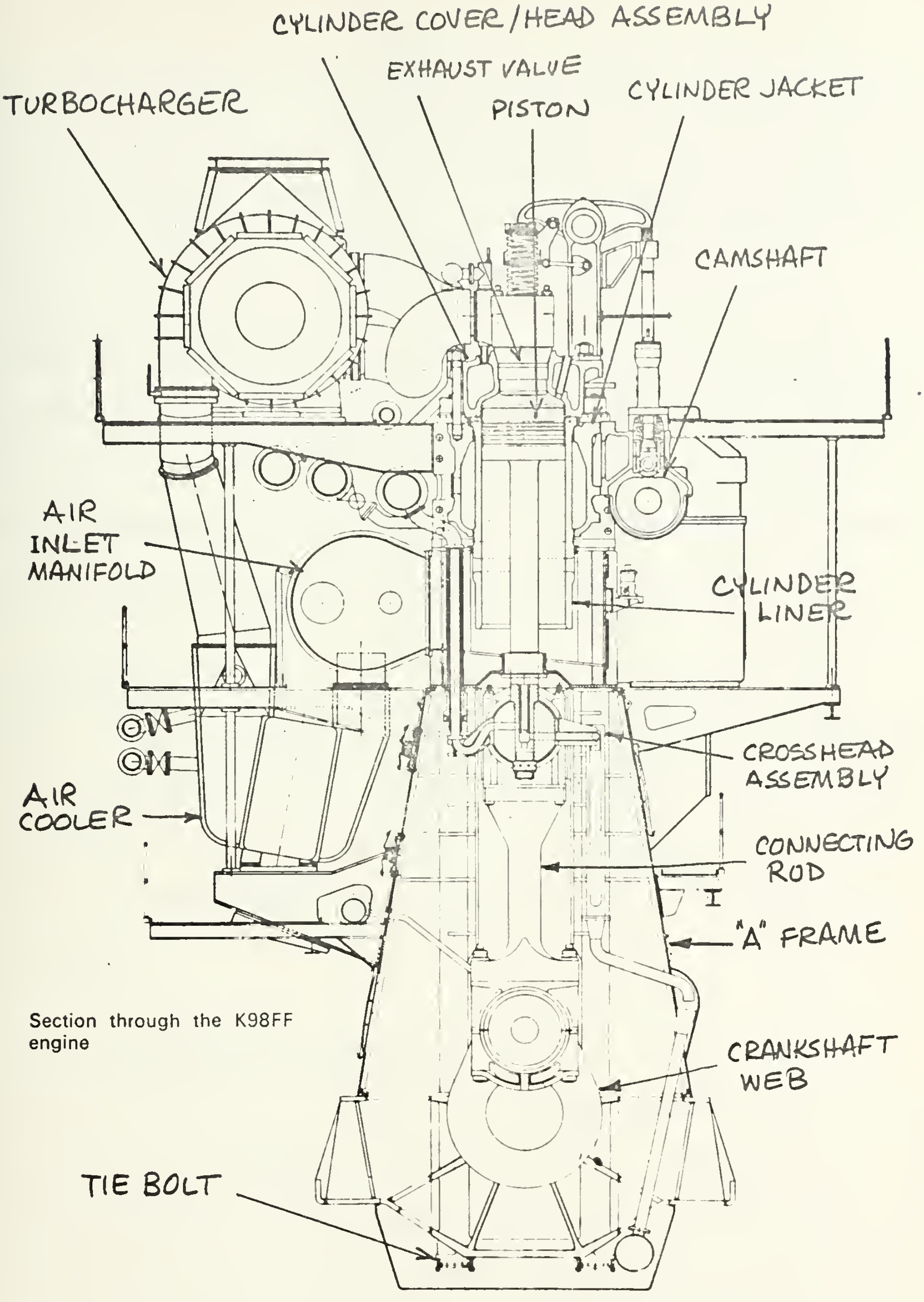
This chapter deals with the particulars of the DDC installation for the low speed diesel engine. Besides a description of the engine (highlighting only those features having impact on the control system), control strategy to be employed, and parameters to be monitored/controlled, typical characteristics of equipment suitable to accomplish the task is presented (data on the equipment was obtained by a survey of manufacturers).

2. The Engine [1,2] (See Figure IV-1.)

2.1 General Data and Arrangement

The K98F engine (of which the 7K98FF engine is a seven cylinder reversible marine version) is a high pressure, turbo-charged, longitudinally scavenged, single acting, two-stroke, crosshead type with centrally arranged exhaust valves in the cylinder covers. Specific data includes:

Number of cylinders	6-12
Bore/stroke (mm)	980/2000
Continuous service output	3350 HP
Rev/min	100
Max. continuous output	3700 HP
Rev/min	103
Approx. weight coefficient*	130
Overall length coefficient*	1920
Width of base (mm)	4920
Overall height (mm)	12950



Section through the K98FF engine

FIGURE IV-1

*Note: (1) Weight of engine (metric tons) = (wt. coeff.) x (no. of cylinders + 1)

(2) Overall length of engine (mm) = (length coeff.) x (no. of cylinders + 2)

The cylinders are divided into two groups, between which is the chain drive for valve motion and fuel pump drive. The scavenging air manifold extends the length of the engine. A characteristic of the engine type is the system of vertical through bolts extending from the top of the cylinder frames down through the scavenging air boxes, A-frames and bedplates.

2.2 Cylinder

Each cylinder liner is suspended in a heavy cast-iron cylinder frame located on top of the scavenging air box. Cooling water (fresh water) for the cylinders flows between the liner and the frame. In the cylinder cover are holes provided for the exhaust valve, indicator cock, and cover cooling water connections.

2.3 Piston/Piston Rod and Crosshead

The pistons are cooled by oil supplied from the forced lubrication system of the engine. The oil is passed to the cooling space of each piston via telescopic pipes leading to the crosshead, through ducts in the crosshead, and up the piston rod through a bored passage. Each piston has six rings. The crosshead bearing surfaces consist of two guide shoes which are white-metal lined with grooves being cut horizontally in the face to ensure an adequate supply of lubricating oil. A piston rod stuffing box and diaphragm arrangement separates the crankcase from the upper part of the engine. Outlet cocks

help detect the condition of the sealing and scraping rings; leakage of air shows that the sealing rings are out of order and an excess oil discharge means that the scraper rings are in need of examination.

2.4 Connecting Rod and Mainbearings

All bearings, i.e., crosshead, bottom-end and top-end of the connecting rod and main bearings, are lubricated from the engine forced-lubrication system. Oil pipes from the supply header are led to the main bearing covers. Thence, the oil passes through radial holes to the longitudinal hole in the crankshaft journal pieces, continuing through holes in the crankwebs and crankpins to the bottom-end bearings. Ascending through the longitudinal holes in the connecting rods, the oil lubricates the top end bearings and guide shoes, and then flows outward into the crankcase.

2.5 Thrustblock

The thrustblock is normally incorporated in the bedplate at the aft end of the engine, but it may be a separate unit if so desired. The thrust block is of the single collar, pivoted-pad type. The thrust bearing is lubricated from the forced lubrication system of the engine.

2.6 Camshaft Chain Drive and Exhaust Valve Actuating Gear

The camshaft which actuates the exhaust poppet valves and the fuel injection pumps is driven from the crankshaft by a transmission system which consists of two roller chains of identical size. The valve actuating cams and rollers are lubricated by oil, which circulates in a closed circuit separate from the pressure-oil system of the engine.

2.7 Exhaust Valve

The exhaust valve is situated at the center of the cylinder cover and is kept closed by two sets of helical springs. The exhaust valve is cooled by fresh water which passes to it from the cylinder cover.

2.8 Fuel Injection Pump, Valves, Regulation and Filtering

Each cylinder has one injection pump which is actuated by the camshaft mentioned previously. Fuel flowing through the pump body keeps it suitably heated. The roller guides of the fuel pumps, and also the valve gear, are lubricated from a special pressure-oil system.

There are two fuel injection valves for each cylinder. The valves are cooled by diesel oil; stored oil from the diesel oil tank is drawn by an electrically-driven pump and circulated through all the fuel valves, thereby forming a separate circuit.

For regulation, each pump plunger has two milled recesses, each limited at one side by a steep helical ridge. Regulation is effected by turning the pump plunger, by which the helical edges alter their position relative to the pump inlet holes.

Between the priming or surcharging pump, and the fuel injection pumps there is arranged a fuel oil filter whose function is to remove extraneous matter from the fuel oil before it reaches the injection pumps and fuel valves.

2.9 Cylinder Lubrication

Each cylinder has its separate lubricator driven by a helical wheel drive from the camshaft. The lubricator consists of a reservoir in which are arranged a number of small pumps, each supplying oil to its designated point

of lubrication.

2.10 Governing/Regulating Gear and Reversing Mechanism

The engine rpm can be varied over all speeds (above minimum) up to the maximum speed of the engine. A hydraulic governor of the Woodward make is provided to maintain approximately constant revolutions in all circumstances. The deflection of the governor is transmitted through a pull-rod arrangement to the fuel pumps. The fuel delivery of these pumps is regulated according to the load. The governor is mounted on the upper chain transmission casing and is driven from the intermediate shaft of the chain drive together with the starting air distributor. In the case of failure, an electric generator fitted on the end of the camshaft actuates a solenoid valve which, through an air cylinder moves the fuel pumps to the no-fuel position. The starting/reversing mechanism positions cams for starting air, fuel pump and exhaust valve timing.

2.11 Turbocharger

For the seven-cylinder engine, scavenging and charging air are supplied by two exhaust-gas driven turbo-compressors. The forward turbocharger supplies cylinders 1-4, and the after, 5-7. Atmospheric air is drawn into the centrifugal compressor through a silencer in which a filter is incorporated. Compressed air passes through a sea water cooler before entering the air manifold on the engine. The turbine is a single-stage unit, as is the centrifugal compressor. The turbocharger is lubricated by its own individual lube oil system.

2.12 Cooling Water Systems

There are two cooling water systems; one is a fresh water system, and the

other, salt water.

The fresh water system cools cylinders, cylinder covers, exhaust valves and the turbo-compressors and includes an elevated head tank and associated electric-driven pumps.

The salt-water system supplies water to the air cooler, the lube oil coolers, the freshwater heat exchanger, and fuel oil and turbocharger oil coolers if installed. A simple schematic of the cooling water systems is shown in Figure IV-2. Duplication of pumps/heat exchangers is not shown.

2.13 Lubrication

There are several individual lube-oil systems as mentioned previously:

Main engine lubrication system: circulates oil from the crankcase sump through a separator and cooler before going to the bearings and cooling the piston.

Cylinder lubrication system: oil is circulated by individual cylinder pumps driven from the main crank by the chain and cam mechanism described earlier.

Camshaft lubricating system: as described earlier, a separate system is used to lubricate the camshaft mechanism.

Turbocharger lubricating system: the turbocharger lubricating system is also a separate system.

A typical simplified system diagram for the lubricating systems described above is shown in Figure IV-3.

2.14 Other Auxiliary Equipment

Other auxiliary equipment includes:

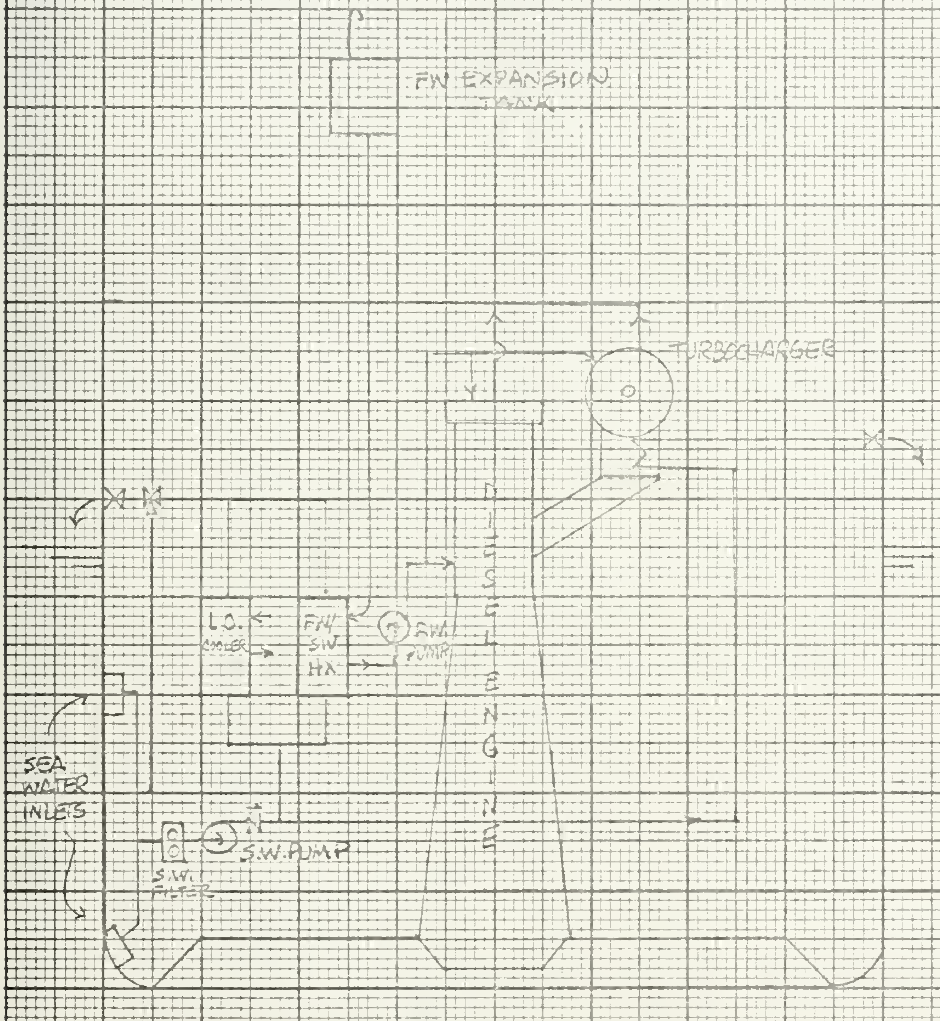


FIGURE IV-2

SIMPLIFIED DRAWING OF COOLING (WATER) SYSTEMS (REDUNDANCY OF PUMPS, HEAT EXCHANGERS, ETC. NOT SHOWN).

Figure IV-2

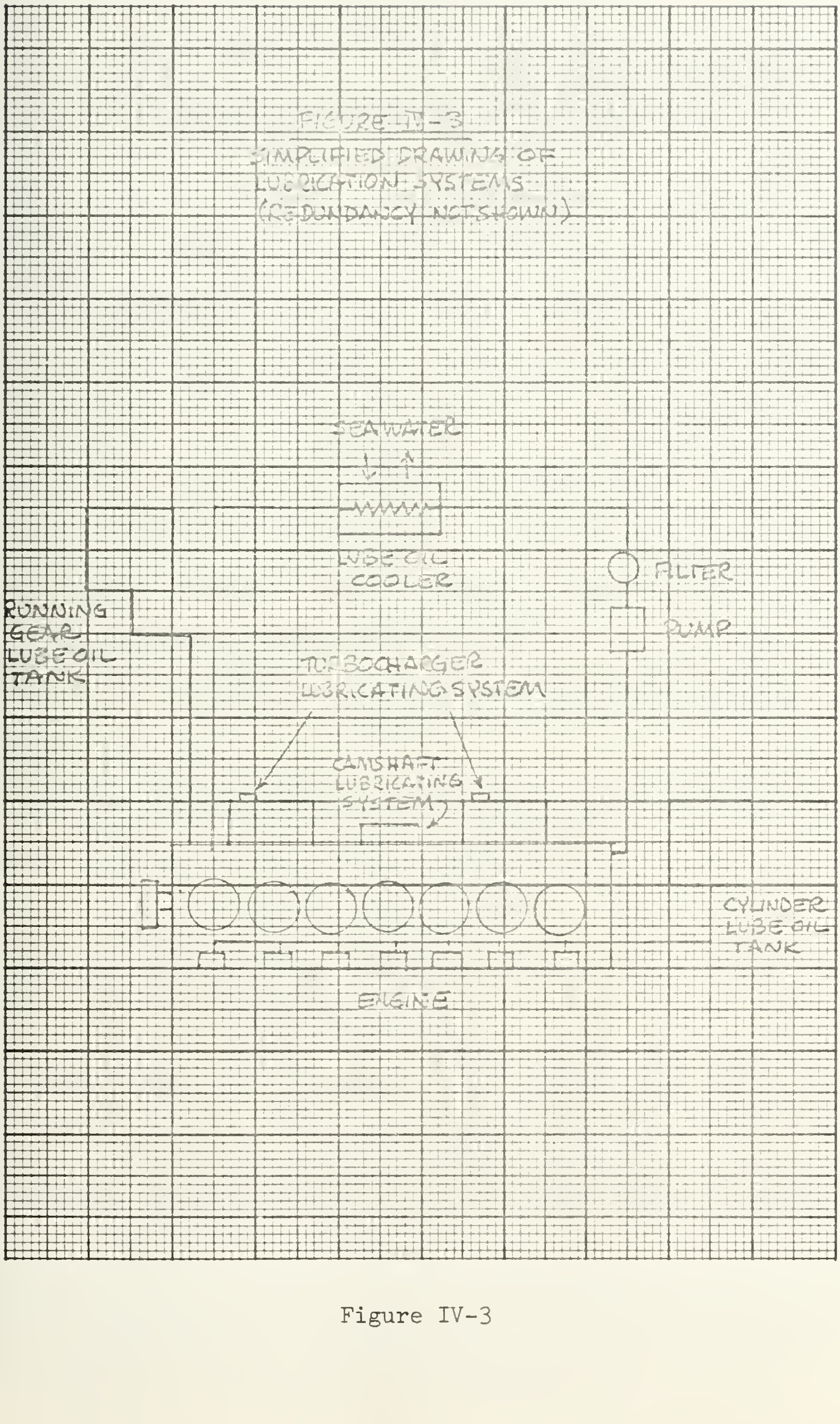


FIGURE IV-3
SIMPLIFIED DRAWING OF
LUBRICATION SYSTEMS
(REDUNDANCY NOT SHOWN)
SEA WATER
LUBE OIL
COOLER
FILTER
PUMP
RUNNING
GEAR
LUBE OIL
TANK
TURBOCHARGER
LUBRICATING SYSTEM
CAMSHAFT
LUBRICATING
SYSTEM
CYLINDER
LUBE OIL
TANK
ENGINE

Figure IV-3

(1) Air compressors (for starting air);

(2) Fuel oil booster pump, preheater, filter and equipment for heavy fuel operation (which may include a filter, separator, several tanks with heaters and one or more pumps).

3. Control Strategy/Functions to be Performed

As discussed in Chapter III, one of the tasks for the system designer is to determine the overall goals of the control system and state explicitly what the control system will accomplish. The goals of the control system should include the achievement of superior economical and technical operation of the diesel propulsion plant. This can be accomplished by "unattended" machinery spaces, and automation only where it will achieve the overall goals (as opposed to unnecessary automation). The following is a list of the proposed functions of the control system:

(a) Monitoring of the plant including detection and indication of alarm conditions.

(b) Logging of plant parameters and conditions at required intervals and indication (display or printout) on demand.

(c) Trend analysis recording and display.

(d) Logging engine orders and responses.

(e) Remote control of plant from bridge.

(f) Automatic control of propulsion plant temperatures, pressures, levels, etc., including auto starting of auxiliary equipments.

(g) Performance of fault analysis and corrective action on alarm conditions.

It was decided not to include: (1) cold plant startup/shutdown sequences due to their complexity and the fact that they could be performed manually

by ship personnel when necessary, and (2) elaborate preventive maintenance evaluation such as used in reference (3).

4. Parameters/Conditions to be Monitored/Controlled

The plant parameters/conditions that should be monitored and/or controlled include:

Main Engine F. W. Cooling System

Pump differential pressure

FW/SW cooler inlet and outlet temperatures

FW expansion tank level

Reserve cooling water tank level (if installed)

Outlet temperature of: (1) each cylinder
(2) each turbocharger

Pump status (on/off)

Main Engine S.W. Cooling System

Injection temperature (i.e., seawater temperature)

Pump differential pressure

FW/SW cooler inlet and outlet temperatures

Lube oil cooler inlet and outlet temperatures

Scavenging air cooler inlet and outlet temperatures, and supply pressure.

Pump status

Engine Lubricating Oil Systems

Main engine pump suction and delivery pressures (or differential pressure)

Cooler inlet and outlet temperatures

Lube oil to engine temperature

Sump tank level

Pressures to and from filters (or differential pressure)

Temperature at each main bearing

Pressure at main engine bearing inlet manifold

Temperature of thrust bearing segment

Pressure of piston cooling oil

Flow at piston cooling oil outlet

Cylinder lube oil pressures and flows

Cylinder lube oil tank level

Turbocharger lube oil tank level

Turbocharger oil pressure and temperatures

Camshaft oil pressure

Pump status

Fuel Injection Valve Cooling System

Pump discharge pressure

Temperature of oil to and from header

Pump status

Main Engine Exhaust Gas System

Temperature of gas leaving each cylinder

Temperature of gas to and from turbochargers

Main Engine Pressure Charging System

Temperature of air at inlet

Air pressure in scavenging receiver

Temperature of air leaving turbocharger

Temperature of air leaving coolers

Turbocharger speed

Turbocharger vibration monitor

Temperature inside scavenge belt

Main Engine Fuel Oil System (less heavy oil section)

Oil pressure before and after high pressure fuel pumps and filter

Fuel oil viscosity

Fuel oil temperature

Booster pump status

Main Engine Starting Air System

Air bank pressure

Pressure in starting air manifold on engine

Compressor status

Other Engine-Related Items

Direction of rotation and speed of shaft (rpm)

Shaft torque

Fire detection monitor

Bilge level

Crankcase monitor

Fuel rack position

Overspeed

Reversing indicator

5. Basic Control System

The basic hardware system for direct digital control of the 7K98FF engine

is shown in Figure IV-4 and discussed below:

Process Inputs--inputs from analog and digital transducers for the monitored/controlled variables discussed previously are passed through signal processing devices, an input multiplexer and analog-to-digital converter (analog inputs only).

Central Processing Unit (CPU)--the capacity of the CPU will be estimated in Chapter V.

Control Room and Bridge Panels--these panels are for display (alarms, conditions, etc.) and informational inputs (engine orders, etc.); the bridge console will contain less capability than the control room, but sufficient for unattended machinery space operation.

Other I/O Equipment--teletypes and/or typewriters can be used for logging and alarm printouts; additional system flexibility is added by having card reader/punch equipment.

Process Outputs--analog and digital control outputs are sent to the propulsion plant (process).

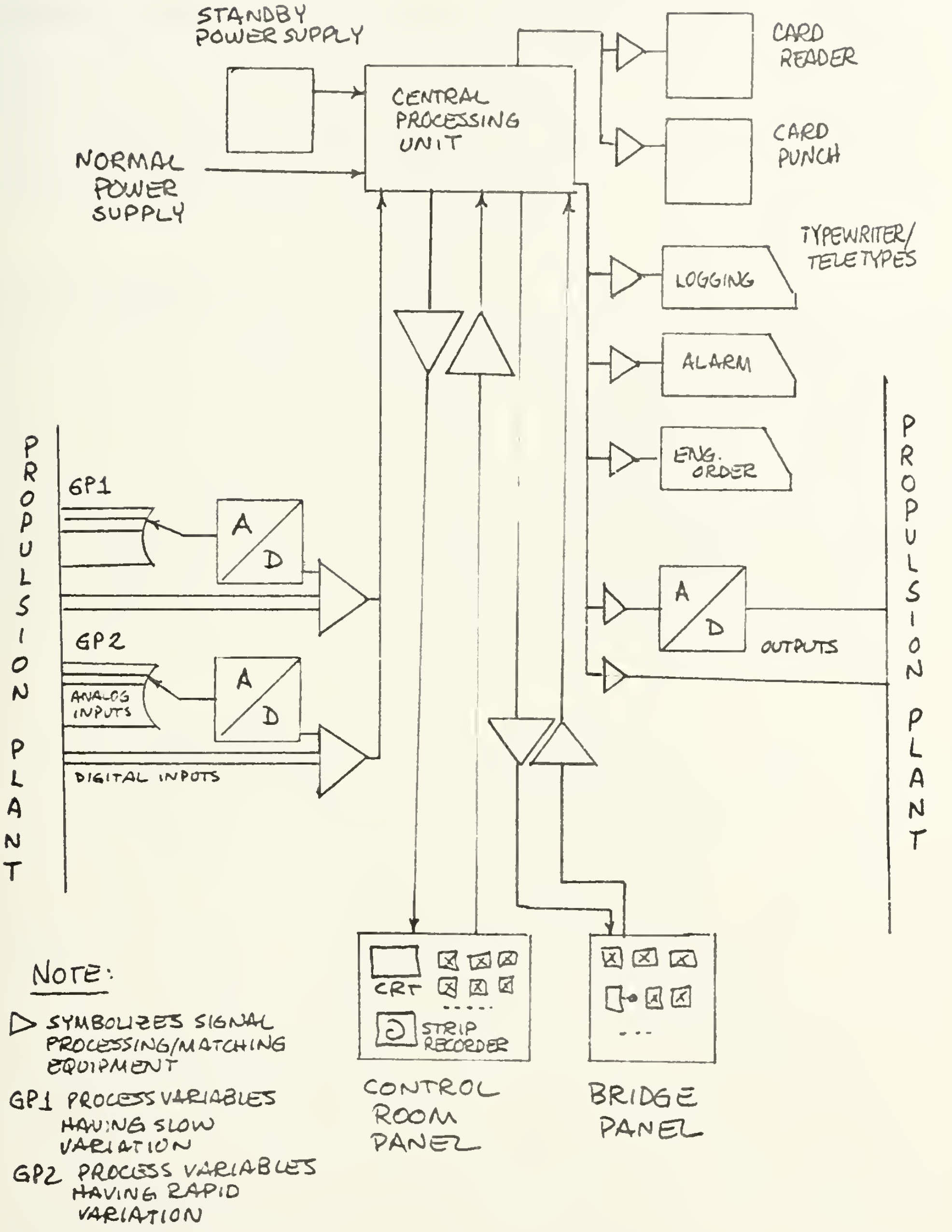
6. Interrupt Hierarchy

The control system must be able to respond rapidly and logically to casualties in the propulsion plant. To accomplish this, a priority list of interrupts based on reference (4) has been devised (see previous discussion of interrupts in Chapter III):

1. System override (to be used only when operator determines safety of the ship is at stake despite other problems).
2. Maneuvering.
3. Low lubricating oil pressure to engine or thrustbearing.
4. High thrust or main bearing temperature.

FIGURE IV-4

BASIC CONTROL SYSTEM HARDWARE



NOTE:

▷ SYMBOLIZES SIGNAL PROCESSING/MATCHING EQUIPMENT

GP1 PROCESS VARIABLES HAVING SLOW VARIATION

GP2 PROCESS VARIABLES HAVING RAPID VARIATION

5. Low level turbocharger lube oil tank.
6. Low flow piston cooling oil outlet.
7. Low lube oil pressure to camshaft.
8. Low cooling water pressure.
9. Excessive turbocharger vibration.
10. High lube oil temperature.
11. High cooling water temperature.
12. Demand printout and trend analysis.

7. Component Hardware Survey

As a part of the design effort, over 100 letters were written to selected manufacturers in an effort to ascertain the availability of components required for accomplishment of the control scheme. Replies were received from approximately 60 of them, and roughly 70% of the material described components thought to be capable of operating in the shipboard propulsion plant environment.

It is to be emphasized that what was accomplished was a survey. The material presented in this report is not intended to be an exhaustive representation of hardware available, but only what is typically found. Matching of individual components (voltage, current impedance, etc.), which may be a difficult problem in practice, was not considered to be within the scope of the project, and therefore was not attempted.

A brief summary of the results is included below, with more detailed specifications contained in Appendix C.

7.1 Sensors

Information was received covering the following sensors:

a. Temperature detectors--resistance temperature detectors (RTD's) and thermocouples.

b. Pressure/differential-pressure transducers--information on a wide variety of devices covering high and low pressure ranges was received.

c. Liquid level--only one response was received, but suitable equipment is manufactured by a number of firms.

d. Other sensors--these include flame detectors, displacement (vibration) probes, torque and thrust meters, and tachometers; as above, a limited number of replies were received, but others manufacture similar equipment.

7.2 Multiplexers and A/D, D/A Converters

A number of firms are engaged in this field and selection is from a variety of products; as in other areas of hardware systems design, it cannot be overstressed that matching of sensors with other "front end" equipment, and the subsequent matching of this equipment with the computer must be addressed in the practical application.

7.3 I/O Devices

A limited number of replies covering teletypes, printers, graphic recorders and CRT's were received, but a large number of product lines in these areas exists on the market. Information on four data logging systems, including those manufactured by Decca and installed aboard a number of ships was covered.

7.4 Central Processors

There are many small process control computers on the market. Unfortunately, most of the ones applied in shipboard use in the past have been of foreign manufacture, and ones covered by this survey are of domestic origin.

7.5 Actuators and Interface Equipment

Actuators and associated interface equipment are highly dependent on terminal equipment selection (valves, etc.), and so the information presented is only a sample of what is available.

7.6 Whole Plant Computer Control Packages

A limited number of firms market process control packages adaptable to customer requirements. Of those replies received in this survey only ASEA's "Dieseldac" and IHI's TCM 24D have had marine application in the past, but others are included to show what is available in industrially originated packages that might be adaptable for marine use in the future.

CHAPTER IV.

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CHAPTER V.

PROGRAM LOGIC

1. General

Design of the logic to implement the previously determined control strategy and functions is the final phase within the scope of this project. It is also as far as a design team could proceed in an actual system design until specific hardware was selected. Based on the strategy, functions to be performed, logic development presented herein, and the sizes of similar projects aboard ships, an estimate of process control computer size to implement this scheme has been made (see Section 6.3).

2. Basic Structure [1,2]

The functions that the computer system is to perform (see Chapter V.) can be grouped into three types: (1) the recording functions; (2) the supervising functions; and (3) the control functions (see Figure V-1). These three types are categorized by the nature of the action taken by the process control computer. If the output is in the form of typed or printed records to be examined later, the computer is said to be performing a recording function. If the output is in the form of signals to the operator, the computer is said to be performing a supervising function. If the output is in the form of signals transmitted to control the process, the computer is said to be performing a control function.

2.1 The Operating System

To sequence and control these three functions, a coordinating routine (called an executive routine, a monitor system, or an operating system) is needed.

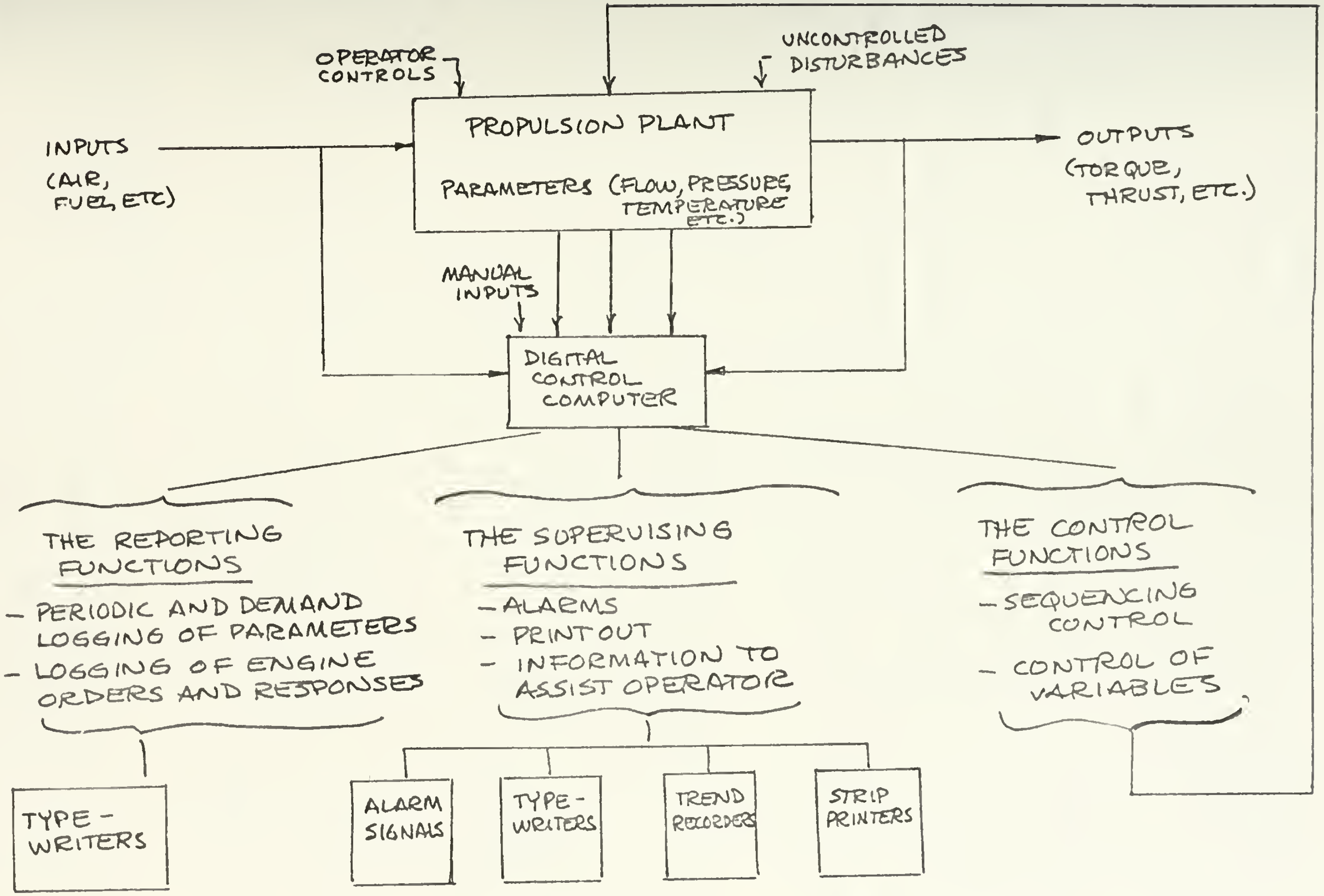


FIGURE V-1

BASIC LOGIC STRUCTURE

The primary tasks assigned to an operating system for on-line control are to schedule and execute the various programmed control assignments, coordinate the servicing of interrupts, supervise I/O activities, analyze and correct computer malfunctions, and oversee bulk-storage transfers.

A block diagram of a representative control computer operating system is shown in Figure V-2, and a flow chart of its operation is presented in Figure V-3. The system has two principal components, a normal mode control routine, and an interrupt mode control routine. Communication between them is accomplished automatically through the computer's interrupt system and the programmed interrupt return.

In the normal mode, a program block scheduler determines the control program that should be executed and then loads and executes it. During execution, a number of I/O control and mathematical function routines are available to the control program. If no control programs are waiting to be run, the system inquires whether other work is waiting, or enters an idle routine. An interrupt (either clock or process) will return program control to the control-program scheduler to reinitiate the control program sequence. Interrupt mode operation requires the interrupt condition to be identified and serviced, and program control returned to the interrupted program.

2.2 The Recording Functions

In performing the recording functions, the computer presents tabulated information ranging from raw data to more complex engineering data. Raw data presentation includes variables of flows, temperatures, and pressures at prescribed intervals, and also printout on operator demand (see Figure V-4).

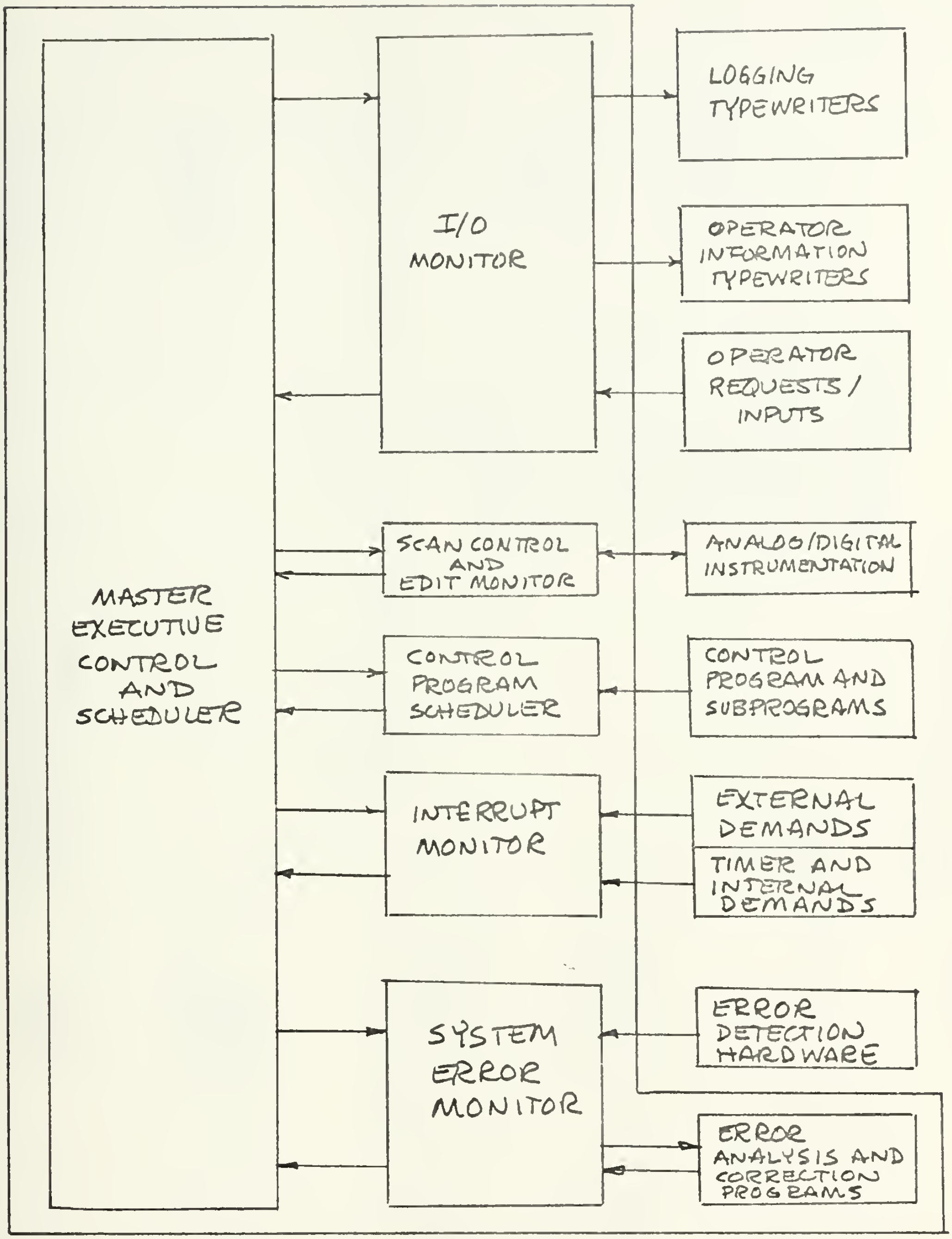

MASTER EXECUTIVE CONTROL AND SCHEDULER
I/O MONITOR
LOGGING TYPEWRITERS
OPERATOR INFORMATION TYPEWRITERS
OPERATOR REQUESTS / INPUTS
SCAN CONTROL AND EDIT MONITOR
ANALOG/DIGITAL INSTRUMENTATION
CONTROL PROGRAM SCHEDULER
CONTROL PROGRAM AND SUBPROGRAMS
INTERRUPT MONITOR
EXTERNAL DEMANDS
TIMER AND INTERNAL DEMANDS
SYSTEM ERROR MONITOR
ERROR DETECTION HARDWARE
ERROR ANALYSIS AND CORRECTION PROGRAMS

FIGURE V-2

BLOCK DIAGRAM OF AN OPERATING SYSTEM FOR A CONTROL COMPUTER

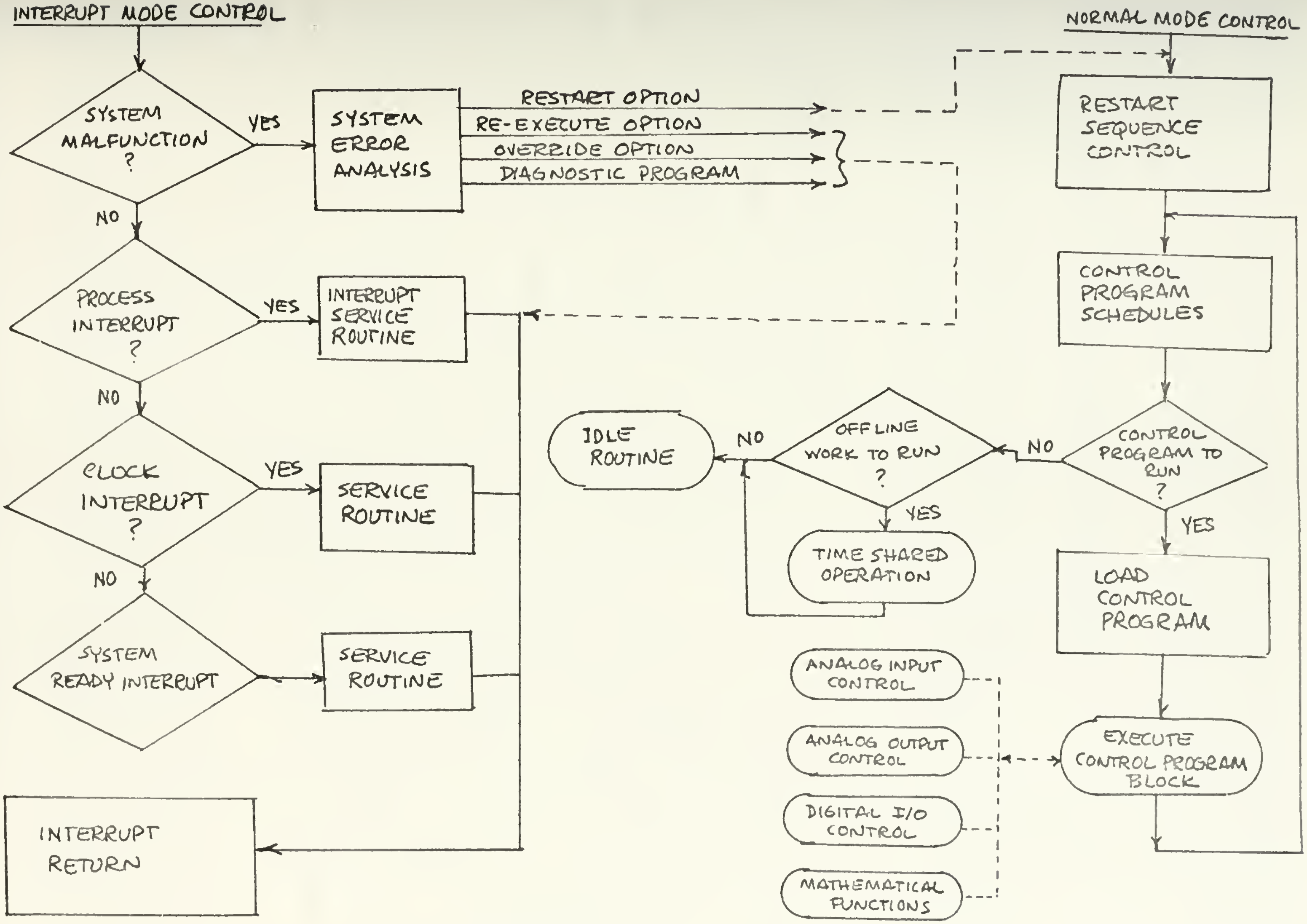


FIGURE VI-3

FLOW CHART OF AN OPERATING SYSTEM
FOR A CONTROL COMPUTER

As proposed in Chapter IV, the recording functions for this scheme include:

a. Logging of plant parameters and conditions at required periodic intervals and on demand.

b. Logging of engine orders and responses.

The logic for these functions is shown in Figures V-5 and V-6. The periodic logging is scheduled by the operating system, while the demand printout is generated by an operator-initiated interrupt.

2.3 The Supervising Functions

In the supervising functions, the computer acts as an important link between the propulsion plant and the operator. The computer scans input voltages that represent physical variables and compares each scanned voltage with the setpoint in its memory. In some cases, the scanned quantity is a bit pattern representing the open and closed states of valves, the "on" or "off" condition of motors, and the like. Visual/audible alarms are given when limits are exceeded, and the alarm values are printed out. Under certain conditions, such as equipment failure, it is desirable to have a history of events preceeding the failure. To do this the computer is programmed to preserve readings over a specified interval.

The supervising functions contribute significantly toward allowing engine operation from the bridge (unattended machinery rooms) or from the control room during abnormal situations or complex evolutions (see Figure V-7).

The supervising functions proposed in Chapter IV include:

a. Monitoring of plant parameters and detection and indication of alarm conditions, including alarms when the rate of increase is too great.

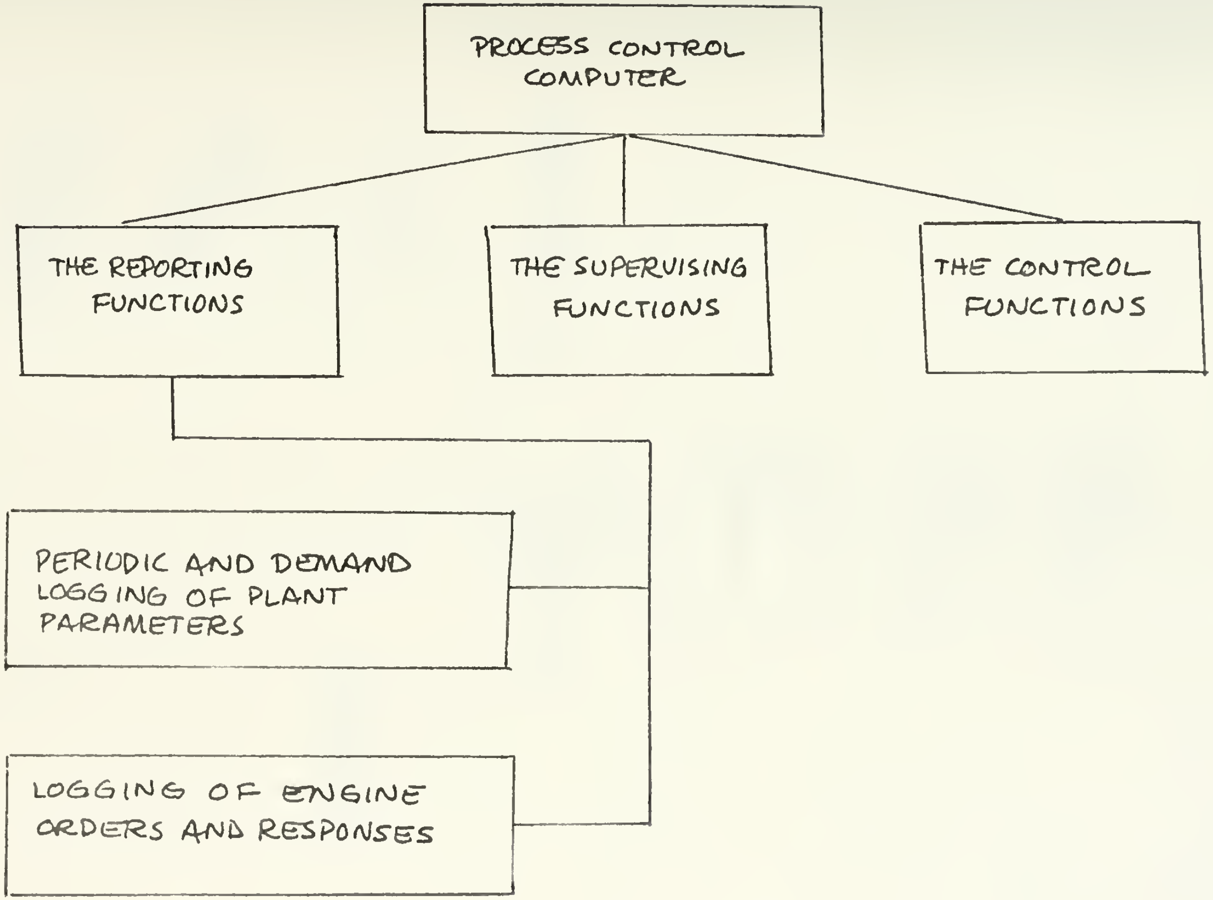
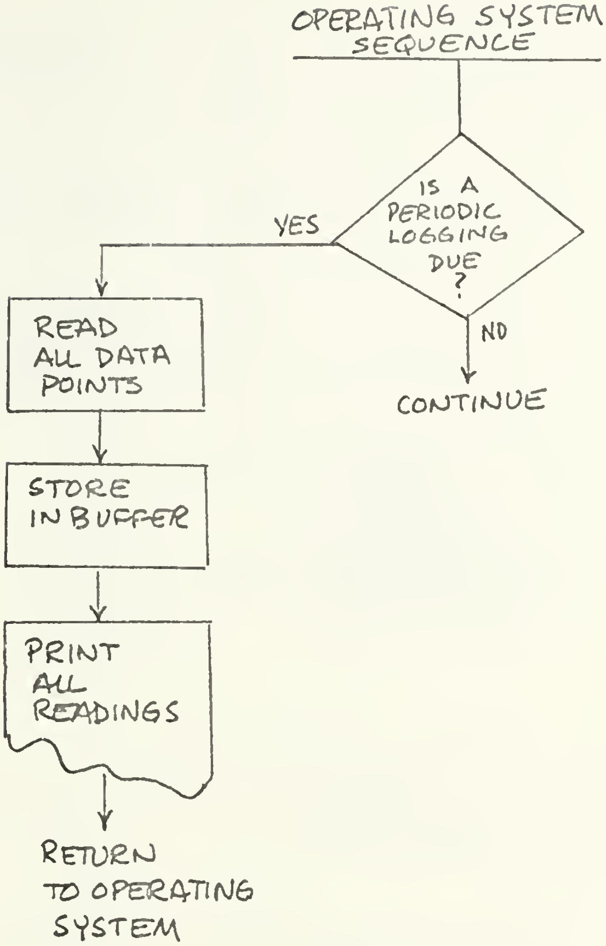

PROCESS CONTROL COMPUTER
THE REPORTING FUNCTIONS
THE SUPERVISING FUNCTIONS
THE CONTROL FUNCTIONS
PERIODIC AND DEMAND LOGGING OF PLANT PARAMETERS
LOGGING OF ENGINE ORDERS AND RESPONSES

FIGURE V-4

THE RECORDING FUNCTIONS

PERIODIC


OPERATING SYSTEM SEQUENCE
IS A PERIODIC LOGGING DUE ?
YES
NO
CONTINUE
READ ALL DATA POINTS
STORE IN BUFFER
PRINT ALL READINGS
RETURN TO OPERATING SYSTEM

DEMAND

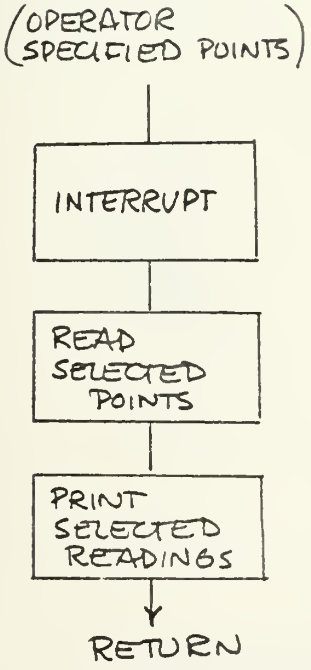


FIGURE V-5

PERIODIC AND DEMAND LOG ROUTINES

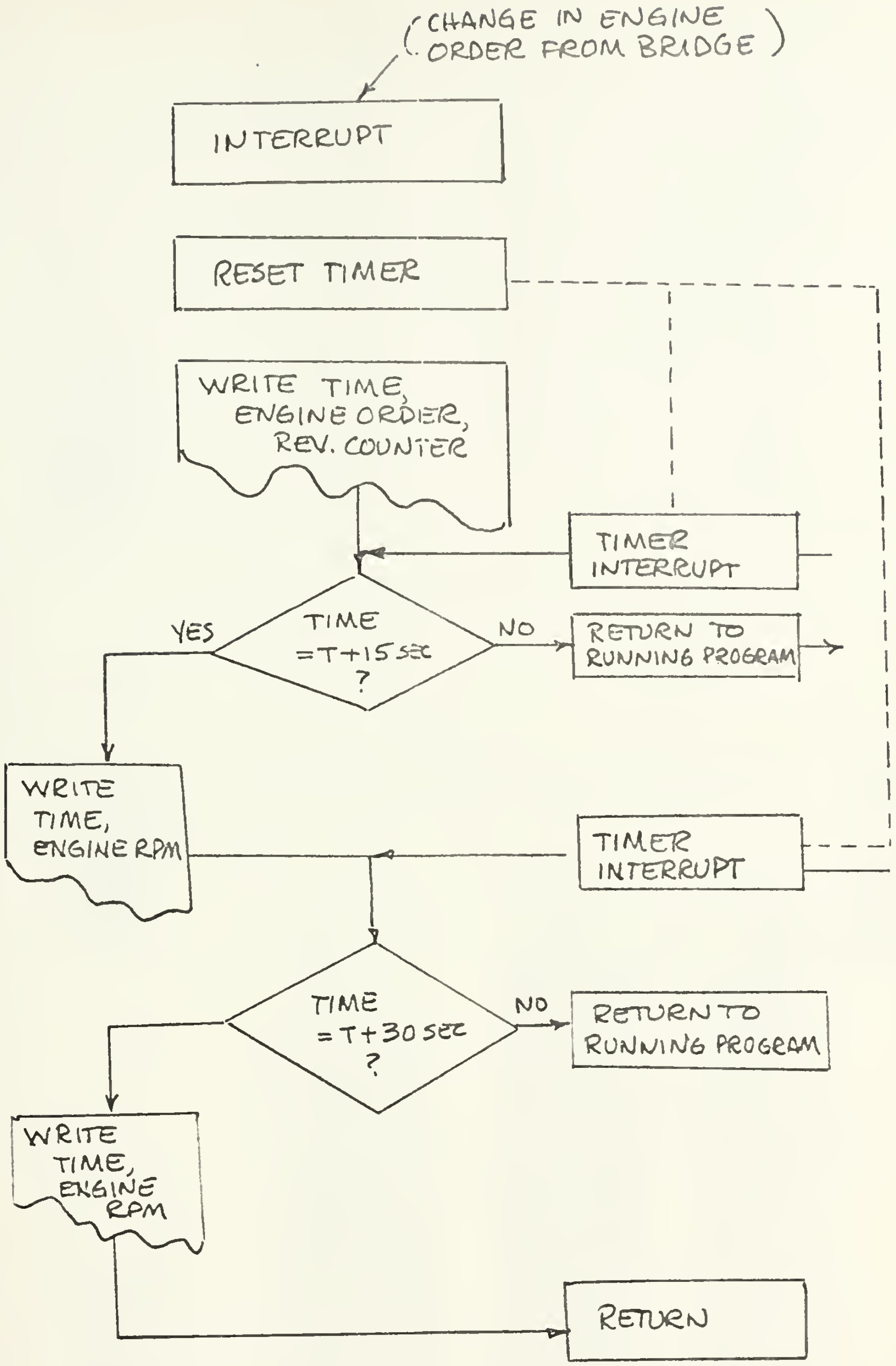


FIGURE V-6

LOGGING OF ENGINE ORDERS AND RESPONSE

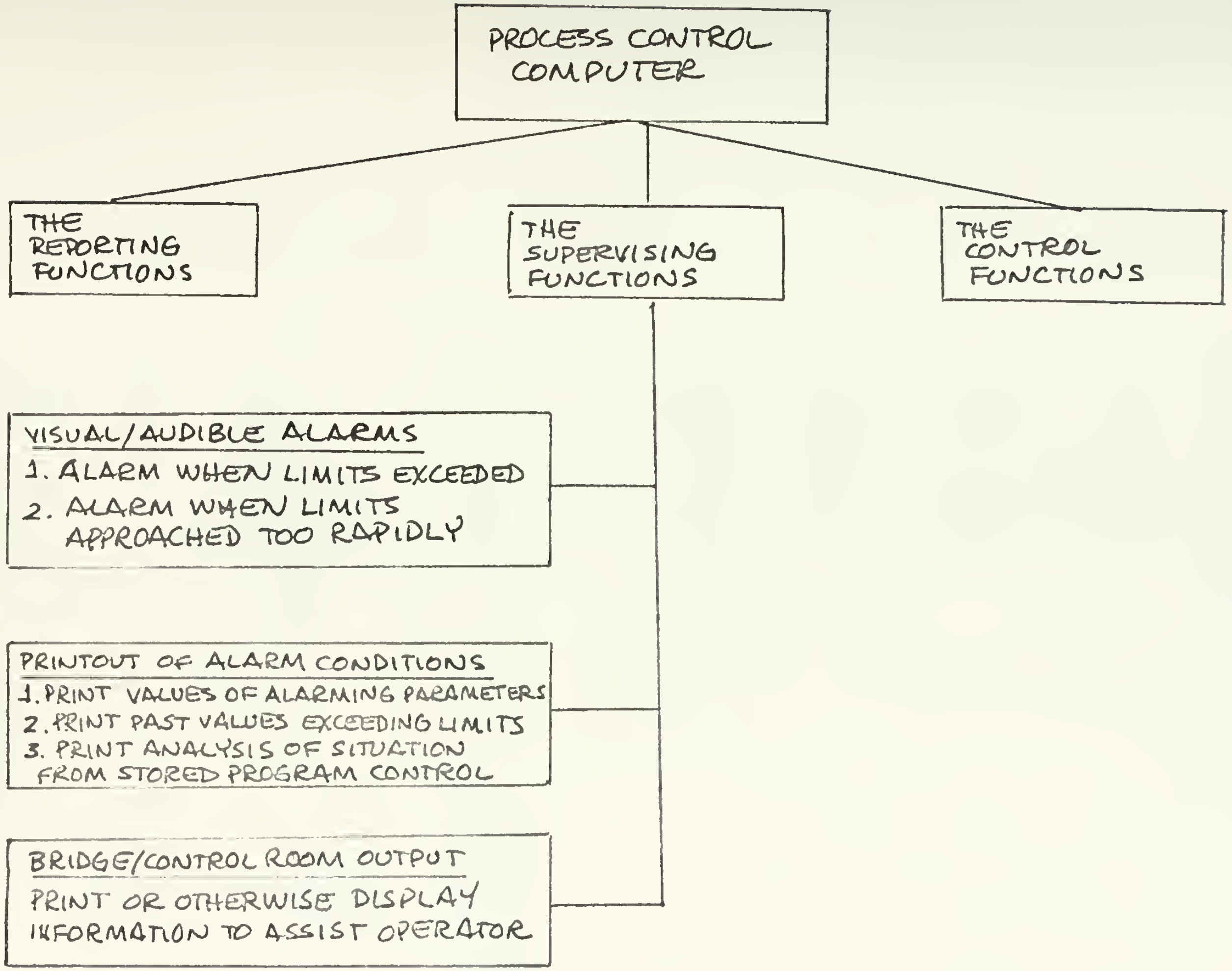

PROCESS CONTROL COMPUTER
THE REPORTING FUNCTIONS
THE SUPERVISING FUNCTIONS
THE CONTROL FUNCTIONS
VISUAL/AUDIBLE ALARMS
1. ALARM WHEN LIMITS EXCEEDED
2. ALARM WHEN LIMITS APPROACHED TOO RAPIDLY
PRINTOUT OF ALARM CONDITIONS
1. PRINT VALUES OF ALARMING PARAMETERS
2. PRINT PAST VALUES EXCEEDING LIMITS
3. PRINT ANALYSIS OF SITUATION FROM STORED PROGRAM CONTROL
BRIDGE/CONTROL ROOM OUTPUT
PRINT OR OTHERWISE DISPLAY INFORMATION TO ASSIST OPERATOR

FIGURE V-1

THE SUPERVISING FUNCTIONS

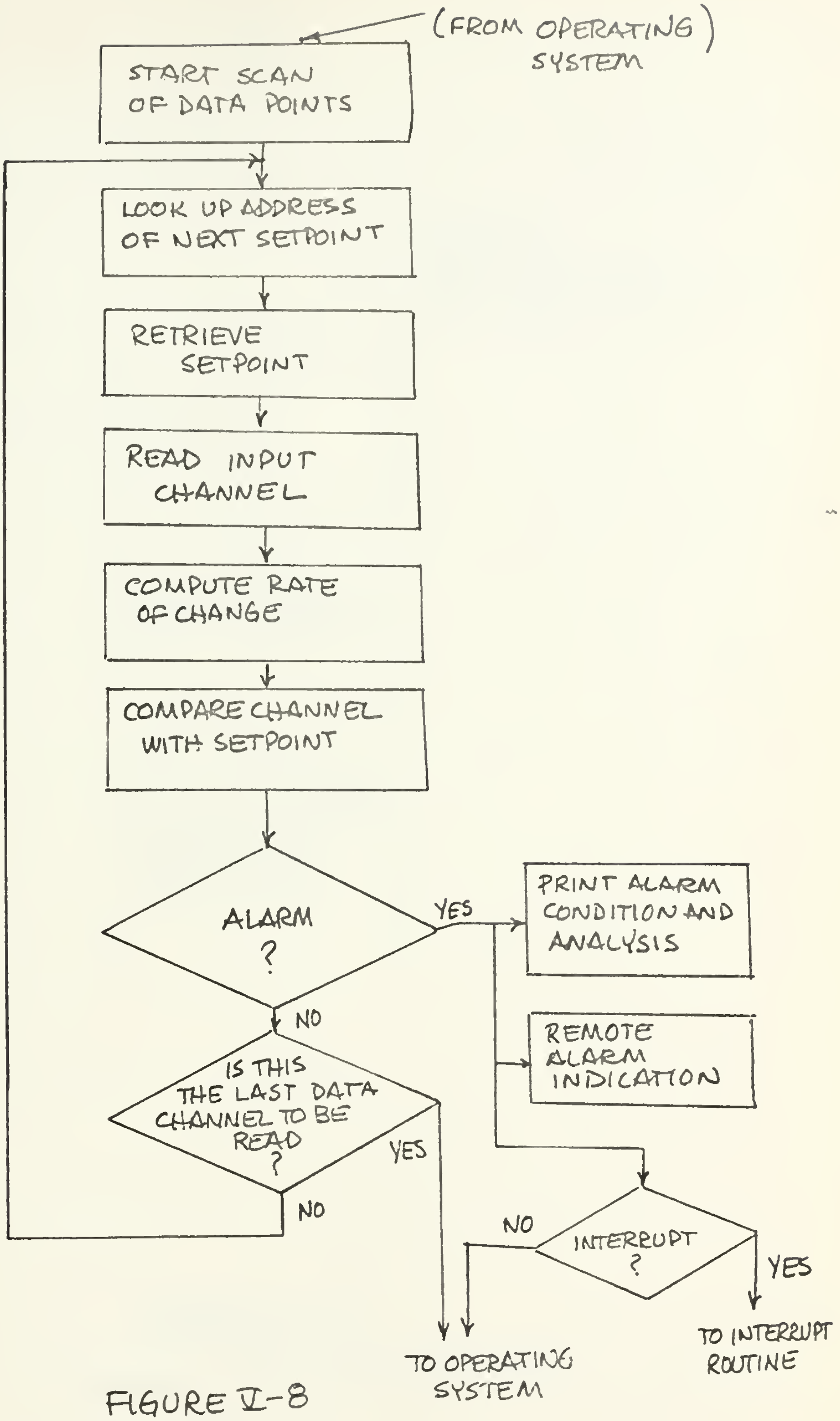


FIGURE V-8

MONITOR AND ALARM ROUTINE

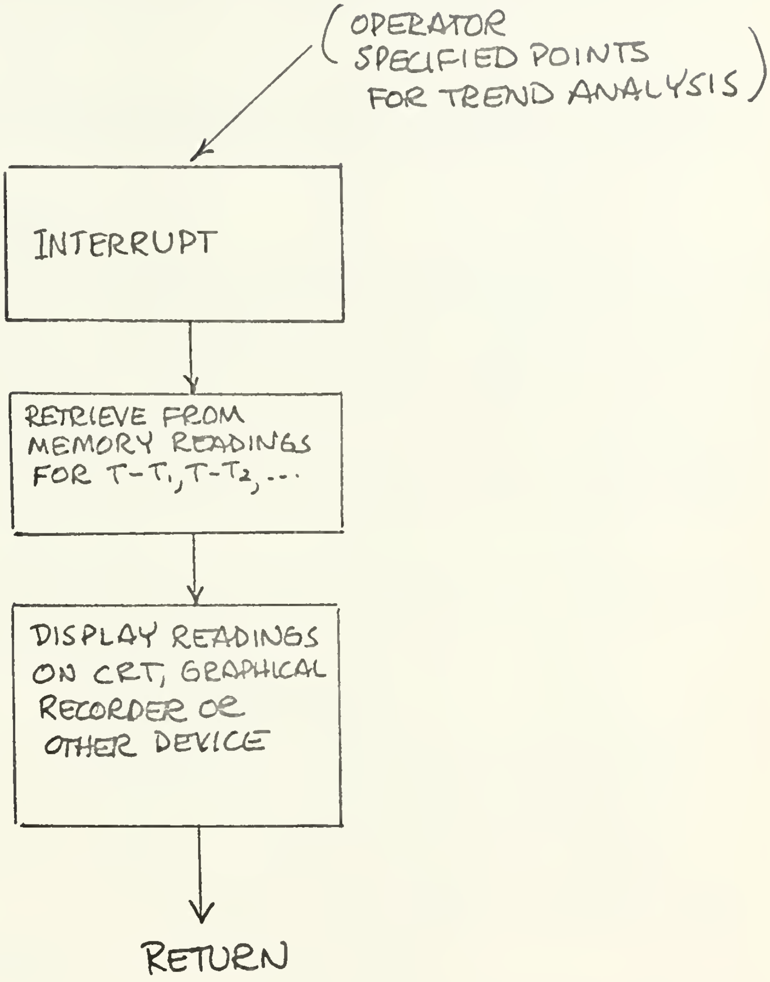

(OPERATOR SPECIFIED POINTS FOR TREND ANALYSIS)
INTERRUPT
RETRIEVE FROM MEMORY READINGS FOR T-T₁, T-T₂, ...
DISPLAY READINGS ON CRT, GRAPHICAL RECORDER OR OTHER DEVICE
RETURN

FIGURE V-9

TREND ANALYSIS RECORDING

b. Printout of alarm conditions including trend analysis.

c. Bridge and control room display of information to allow control of the plant remotely.

The logic for the supervisory functions are shown in Figures V-8 and V-9.

2.4 The Controlling Functions

The two sub-types of the control functions used in this scheme can be called sequencing and variable control. The former involves emergency action procedures, simple startup/shutdown and maneuvering. The latter is the familiar problem of closed loop control of interacting or non-interacting variables.

The emergency actions involving diesel shutdown or slowdown are in accordance with reference (3) and are listed below:

Shutdown	Slowdown
Low lube oil pressure to main engine and thrust bearing.	Low lube oil pressure to main engine and thrust bearing.
High temperature of thrust bearing segment.	High temperature of thrust bearing segment.
Low level in turbocharger oil tank.	Low flow piston cooling oil outlet.
	Low pressure lube oil to camshaft.

It is assumed that when the same condition results in a slowdown and/or shutdown, Burmeister and Wain intends that the latter be initiated at a more severe condition (i.e., lower pressure or higher temperature) than the former. Subsequent followup action shown in Figures V-11 through V-13 such as starting of the standby lube oil pump on the low lube oil pressure

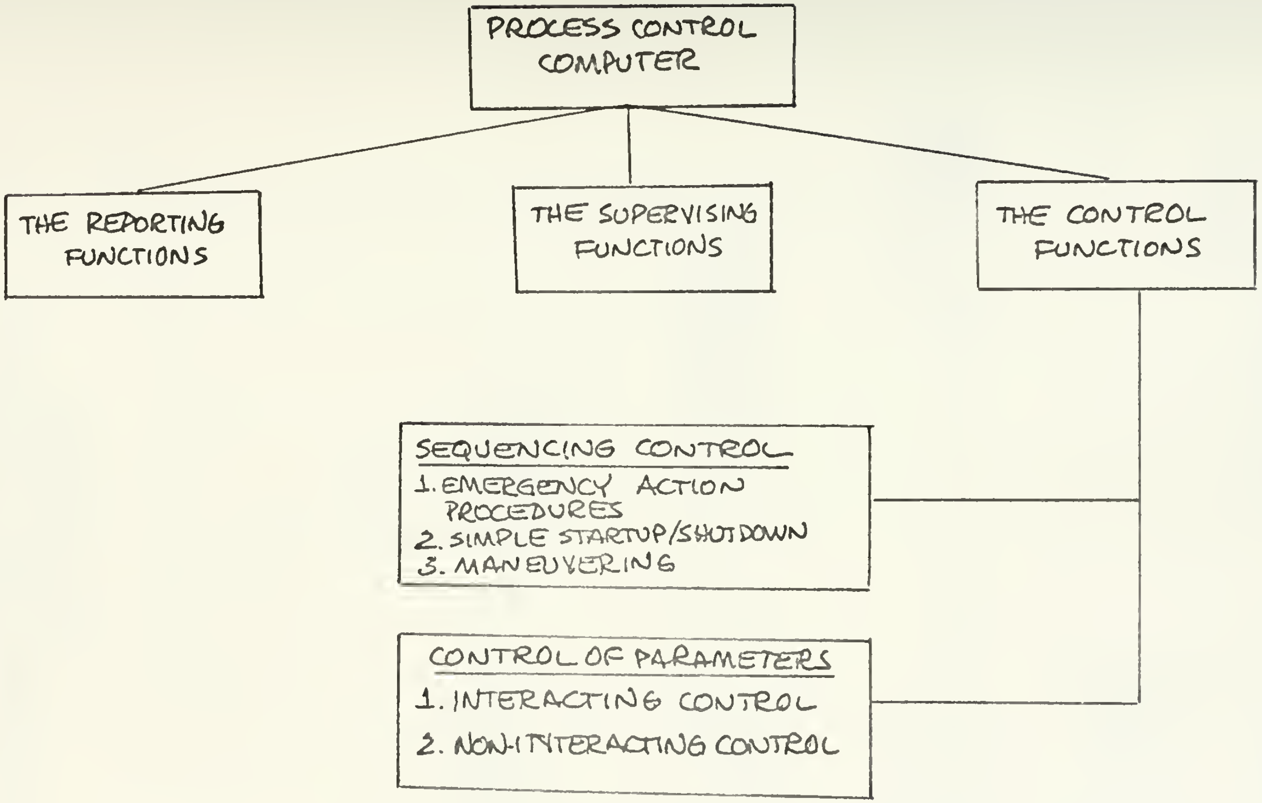


FIGURE V-10

THE CONTROL FUNCTIONS

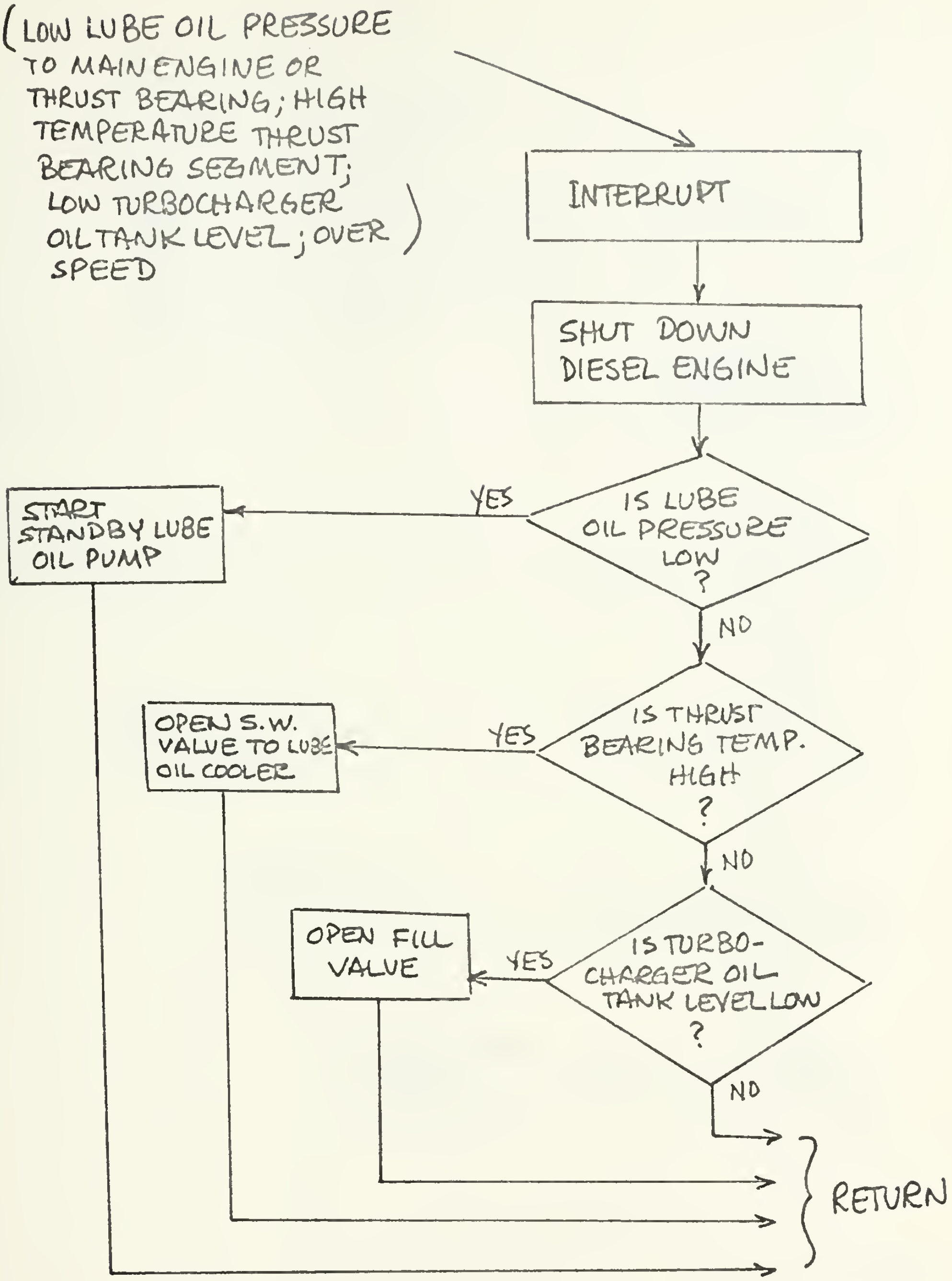

(LOW LUBE OIL PRESSURE TO MAIN ENGINE OR THRUST BEARING; HIGH TEMPERATURE THRUST BEARING SEGMENT; LOW TURBOCHARGER OIL TANK LEVEL; OVER SPEED)
INTERRUPT
SHUT DOWN DIESEL ENGINE
IS LUBE OIL PRESSURE LOW ?
YES
START STANDBY LUBE OIL PUMP
NO
IS THRUST BEARING TEMP. HIGH ?
YES
OPEN S.W. VALVE TO LUBE OIL COOLER
NO
IS TURBO-CHARGER OIL TANK LEVEL LOW ?
YES
OPEN FILL VALVE
NO
RETURN

FIGURE V-11

EMERGENCY ACTION PROCEDURES - DIESEL SHUTDOWN

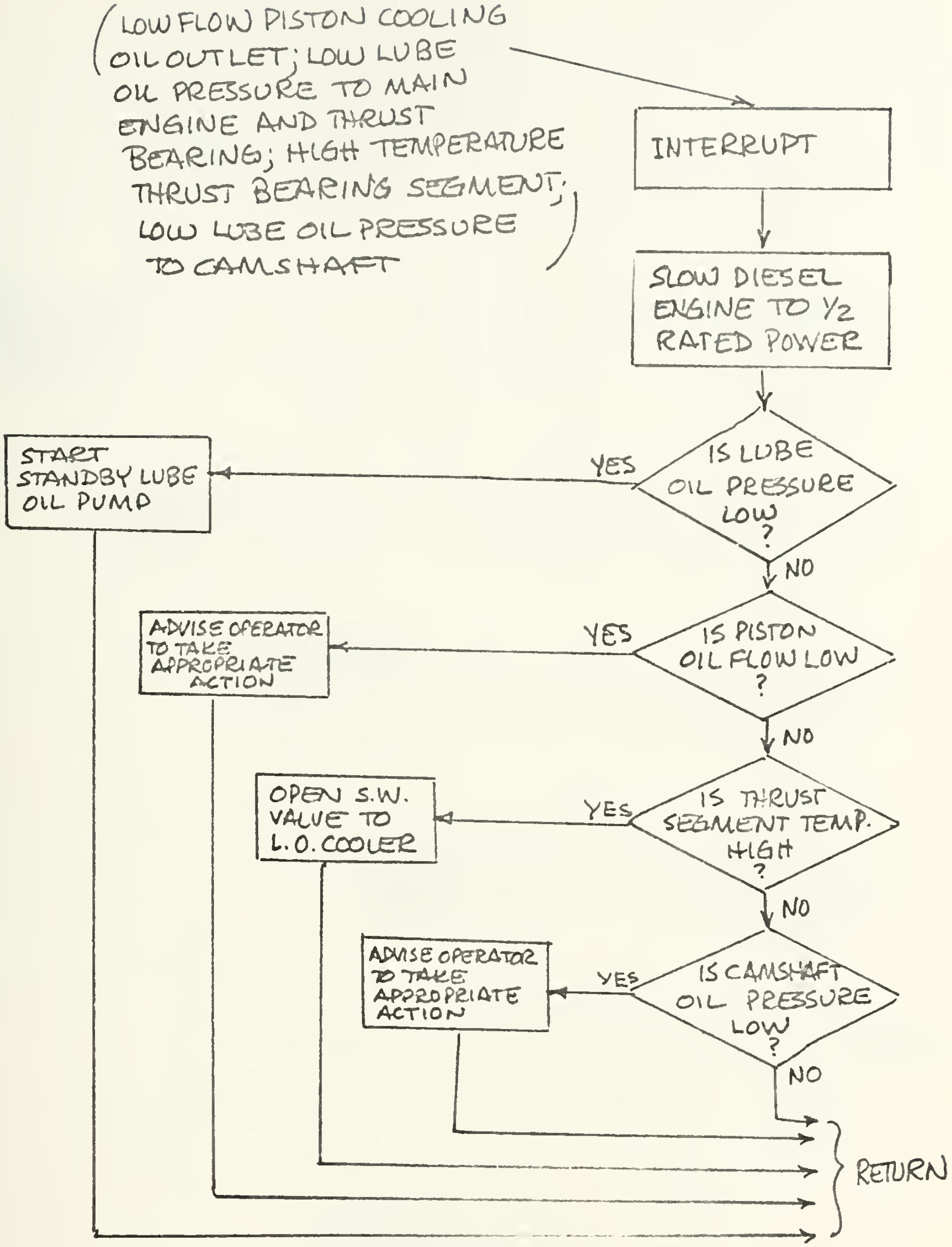

LOW FLOW PISTON COOLING OIL OUTLET; LOW LUBE OIL PRESSURE TO MAIN ENGINE AND THRUST BEARING; HIGH TEMPERATURE THRUST BEARING SEGMENT; LOW LUBE OIL PRESSURE TO CAMSHAFT
INTERRUPT
SLOW DIESEL ENGINE TO 1/2 RATED POWER
IS LUBE OIL PRESSURE LOW ?
YES
START STANDBY LUBE OIL PUMP
NO
IS PISTON OIL FLOW LOW ?
YES
ADVISE OPERATOR TO TAKE APPROPRIATE ACTION
NO
IS THRUST SEGMENT TEMP. HIGH ?
YES
OPEN S.W. VALUE TO L.O. COOLER
NO
IS CAMSHAFT OIL PRESSURE LOW ?
YES
ADVISE OPERATOR TO TAKE APPROPRIATE ACTION
NO
RETURN

FIGURE V-12

EMERGENCY ACTION PROCEDURES - DIESEL SLOWDOWN

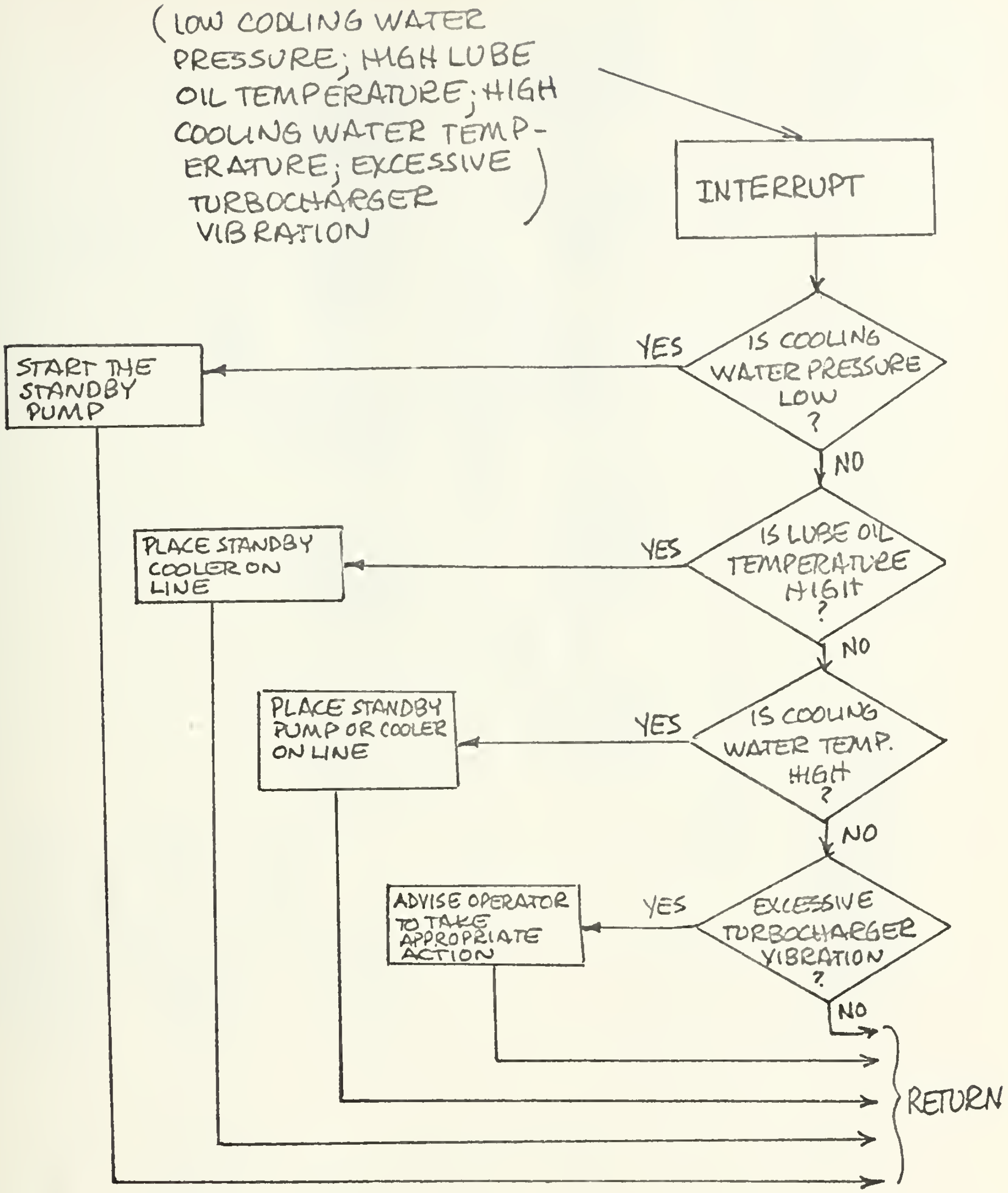

(LOW COOLING WATER PRESSURE; HIGH LUBE OIL TEMPERATURE; HIGH COOLING WATER TEMPERATURE; EXCESSIVE TURBOCHARGER VIBRATION)
INTERRUPT
IS COOLING WATER PRESSURE LOW ?
YES
START THE STANDBY PUMP
NO
IS LUBE OIL TEMPERATURE HIGH ?
YES
PLACE STANDBY COOLER ON LINE
NO
IS COOLING WATER TEMP. HIGH ?
YES
PLACE STANDBY PUMP OR COOLER ON LINE
NO
EXCESSIVE TURBOCHARGER VIBRATION ?
YES
ADVISE OPERATOR TO TAKE APPROPRIATE ACTION
NO
RETURN

FIGURE VI-13

EMERGENCY ACTION PROCEDURES-
NO IMMEDIATE EFFECT ON ENGINE

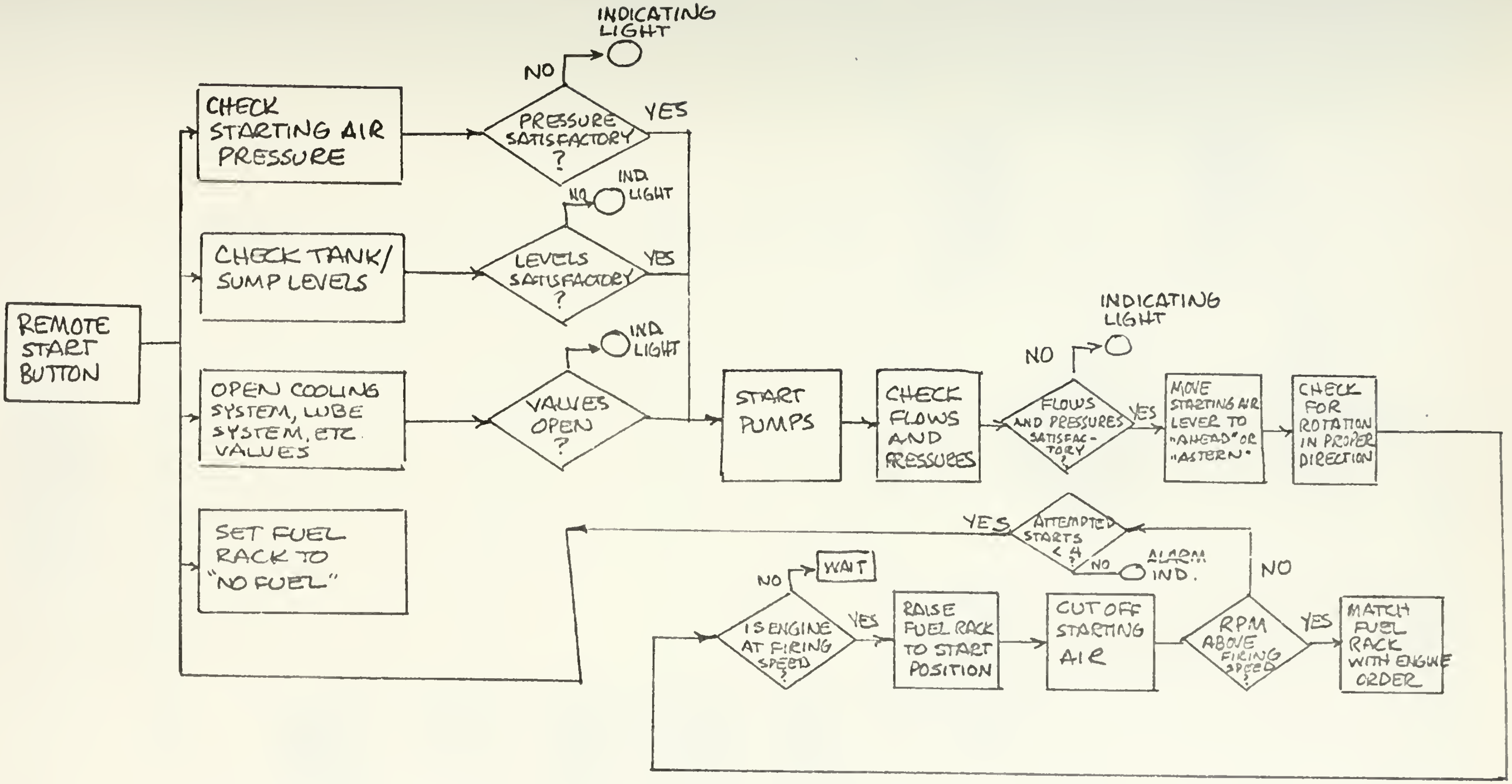

REMOTE START BUTTON
CHECK STARTING AIR PRESSURE
CHECK TANK/ SUMP LEVELS
OPEN COOLING SYSTEM, LUBE SYSTEM, ETC. VALUES
SET FUEL RACK TO "NO FUEL"
PRESSURE SATISFACTORY ?
NO
INDICATING LIGHT
YES
LEVELS SATISFACTORY ?
NO
IND. LIGHT
YES
VALUES OPEN ?
IND. LIGHT
START PUMPS
CHECK FLOWS AND PRESSURES
FLOWS AND PRESSURES SATISFACTORY ?
NO
INDICATING LIGHT
YES
MOVE STARTING AIR LEVER TO "AHEAD" OR "ASTERN"
CHECK FOR ROTATION IN PROPER DIRECTION
ATTEMPTED STARTS < 4 ?
YES
NO
ALARM IND.
IS ENGINE AT FIRING SPEED ?
NO
WAIT
YES
RAISE FUEL RACK TO START POSITION
CUT OFF STARTING AIR
RPM ABOVE FIRING SPEED ?
NO
YES
MATCH FUEL RACK WITH ENGINE ORDER

FIGURE VI-14

SIMPLE STARTUP

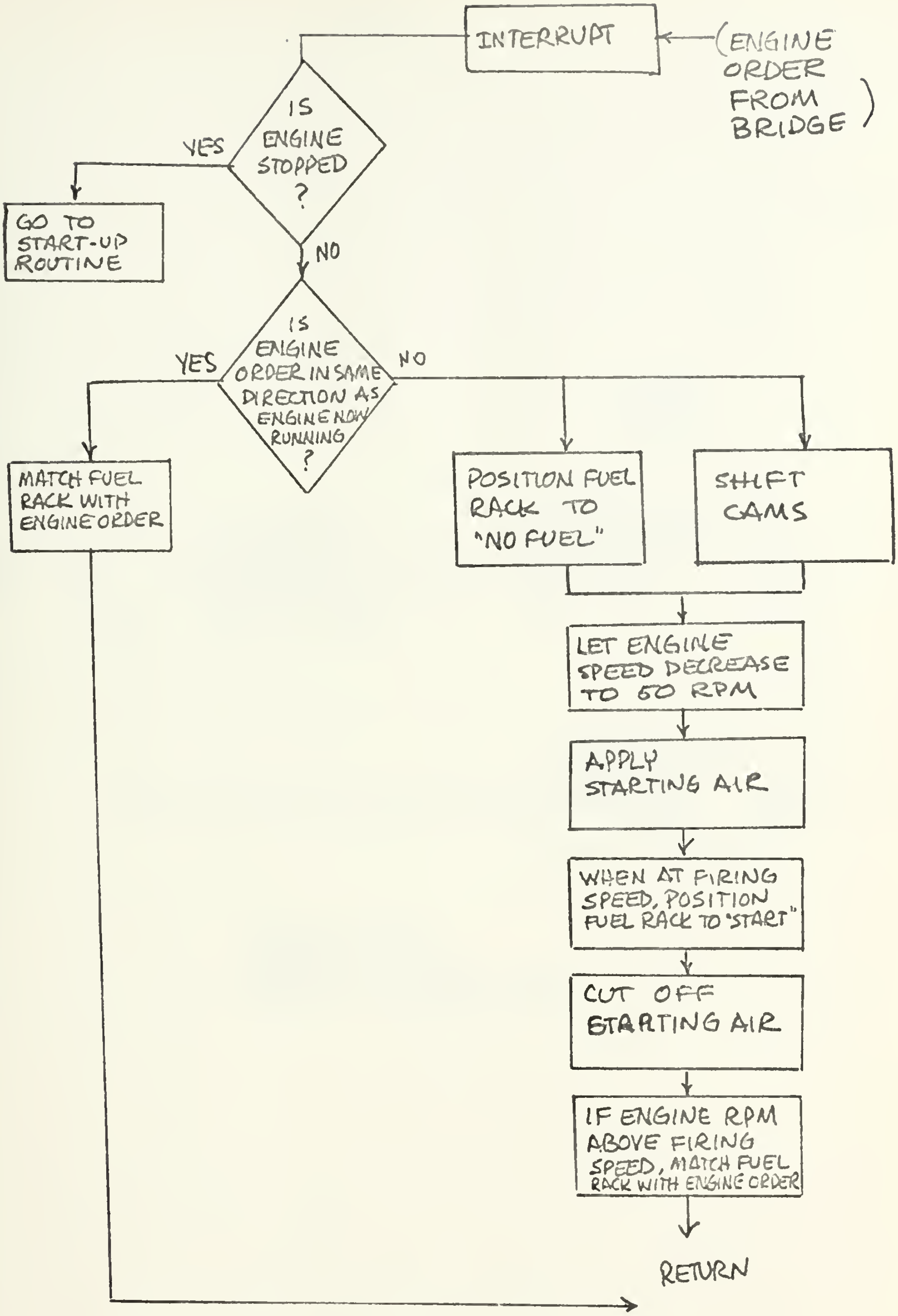

INTERRUPT
(ENGINE ORDER FROM BRIDGE)
IS ENGINE STOPPED ?
YES
NO
GO TO START-UP ROUTINE
IS ENGINE ORDER IN SAME DIRECTION AS ENGINE NOW RUNNING ?
YES
NO
MATCH FUEL RACK WITH ENGINE ORDER
POSITION FUEL RACK TO "NO FUEL"
SHIFT CAMS
LET ENGINE SPEED DECREASE TO 50 RPM
APPLY STARTING AIR
WHEN AT FIRING SPEED, POSITION FUEL RACK TO "START"
CUT OFF STARTING AIR
IF ENGINE RPM ABOVE FIRING SPEED, MATCH FUEL RACK WITH ENGINE ORDER
RETURN

FIGURE V-15

MANEUVERING.

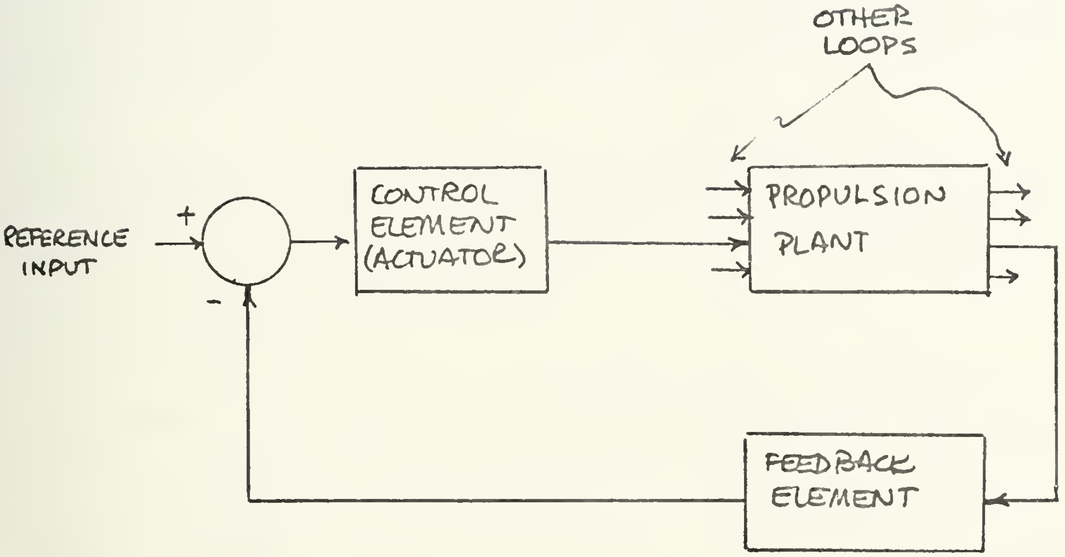


FIGURE VI-16

TYPICAL CLOSED LOOP

casualty is not explicitly stated in reference (3) but is suggested by good engineering practice.

Several other emergency action procedures involving no immediate shutdown or slowdown are included in Figure V-13. On some unattended machinery space installations, these conditions lead to engine slowdowns, but since reference (3) did not specify such, this feature was not specified, but temporary corrective action was incorporated.

Simplified logic for startup following a short duration shutdown is shown in Figure V-14. A more detailed delineation would require knowledge of a specific plant configuration.

Logic for maneuvering is shown in Figure V-15. Due to the nature of the large bore, low speed engine and the practice by Burmeister and Wain of using a Woodward governor for speed regulation, a complicated control scheme for maneuvering and speed control is not necessary.

Closed loop control of other plant parameters is accomplished in standard fashion (see Figure V-16). The control algorithm used in each loop would be dependent on hardware and the parameter being controlled.

3. Estimate of Process Control Computer Size.

Determination of the central processor size required for a control application depends on several factors; among the more important are the functions to be performed, the number of points to be monitored, the speed with which the points are scanned, the size and complexity of the interrupt system, and the skill and efficiency of the programmer.

The accuracy of any estimate of the size required will depend on the level to which the programming has been developed. If the programs have been full written in machine or higher level language, rules of thumb such as the following for Fortran, 8 bits/byte, 4 bytes/word can be utilized:

DO STATEMENT	15 bytes
IF STATEMENT	12 bytes
GO TO STATEMENT	4 bytes
ARITHMETIC OPERATION	4 bytes/operation

In making an estimate based on the level of logic development of this report, such rules are of little value.

A rough estimate of the CPU size can be made by comparing the proposed control scheme contained herein with known sizes of systems now in use. Using the computer systems discussed in Chapter I as a reference, it is estimated that implementation of the control system proposed in this report would require a memory size of 10-12K words.

CHAPTER V.

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CHAPTER VI.

ADDITIONAL CONSIDERATIONS

1. General

The procedure used in this paper to devise a computer control scheme for a low speed diesel engine forms only a part of the procedure that would be used in an actual installation involving perhaps far more than just the engine itself, i.e., electric power generation, navigation, cargo handling, etc. The procedure was of necessity abbreviated, and the scope limited so that one person could carry out the task in a reasonable time frame; the problem was simplified and certain vital considerations were not included. The purpose of this chapter is to explicitly state some of these additional considerations that the design team must reckon with in an actual control system design.

2. The Systems Engineering Approach [1]

The "systems engineering" approach to planning a computer control system is commonly used in other computer applications, and may require modification for use in the design of a shipboard computer controlled system, but is presented here for informational purposes as being a useful method. It views the problem as consisting of several major phases:

a. The Preliminary-Study Phase

In this phase, a variety of subtasks are addressed including:

(1) Management orientation--ensuring higher management has been "educated" so that it may carry out its functions with the project in mind.

(2) Specification of scope and goals--as emphasized previously,

this function must be performed early in the project.

(3) Establishment of project administration--the success of the project may well depend on personnel assigned and the manner in which they are organized.

(4) Project-team orientation--training of the team by contractors may be required.

(5) Technical survey--gaining a thorough understanding of the systems to be controlled, operating procedures and the like.

(6) Economic survey--establishment of the economic feasibility of the project; identification of the areas with the greatest potential return.

(7) Specification of computer functions--formulation of a general operating and control strategy for the computer; enumeration of computational tasks (areas of control, reporting, etc.).

(8) Evaluation and approval--an important check point to ensure further effort will be worth the cost.

b. Equipment Planning Phase

This phase includes:

(1) Preliminary computer system specifications--development of an approximate configuration of the computer system.

(2) Equipment location--deciding where major components will be located.

(3) Establishment of data requirements--determining parameters to be monitored and controlled.

(4) Survey of installed instruments--applicable only to systems that are to be modified.

(5) Determination of supplemental instrument requirements--same as (4) above.

(6) Determination of equipment modifications and their costs.

(7) Planning computer inputs and outputs--detailed planning of system inputs and outputs; signal processing and transmission requirements; man-machine interface requirements.

(8) Instrumentation specification--determination of size, range, response characteristics, sensitivity and signal level as applicable; determination of cost.

(9) Planning of instrumentation installation and configuration--determination of component location; detailed signal level specifications, filtering requirements, A/D conversion rate, interrupt priorities; CPU storage size, speed, registers and instructions.

(10) Computer system pricing--self explanatory.

(11) Evaluation and final approval--a key go/no-go point.

c. Application-Development Phase

This phase addresses many of the more creative problems in system design including:

(1) Computer training--contractor courses for operating personnel and programmers as necessary.

(2) Preparation of off-line programs--programs for process modeling, data analysis techniques, and the like.

(3) On-line program training--to acquaint programmers and operators with executive routines, monitor programs, scanning and logging routines, etc.

(4) Collection and analysis of data--collection of needed data beyond that obtained during the technical survey.

(5) Model development or refinement--sometimes an ongoing task or perhaps utilizing an already existent model.

(6) Development of recording and reporting functions--development of output reporting content and format.

(7) Development of operating and control strategy--construction in detail of logic and control strategy.

(8) Development of process-monitoring functions--given specific instruments, control system configuration, and operating strategy, process monitoring details can be determined.

(9) Planning of on-line tests--to check out the model and the entire computer control scheme.

(10) Programming of on-line operation--after the computer functions have been developed, they must be programmed.

(11) Testing of programs--self explanatory.

(12) Training of operators--particular emphasis should be placed on the man-machine interface.

d. Installation Phase

The final phase before operations includes:

(1) Confirmation of computer specifications--includes final configuration and delivery dates.

(2) Order instrumentation--self explanatory.

(3) Modify the process--as applicable.

(4) Install instrumentation, test and calibrate--an important step.

(5) Construction planning--details of the physical installation are put on plans.

(6) Installation of interface units--self explanatory.

(7) Installation and testing of computer system--often performed by contractor personnel.

e. Operational Phase

This phase includes refinement of I/O data and format, maintenance requirements and a host of other items as the system (and operators) are broken in; it is a shakedown period. Only after this gradual phase-in period can the system be truly called operational.

The above phases are shown in flow diagram form in Figure VI-1.

3. Economics[2]

Although an economic analysis is not a part of this project, computer control of an actual propulsion plant must face the same scrutiny as any other project which competes for limited investment funds and personnel. The extent of computer control, direct digital or otherwise, and the decision of whether to install a computer system at all depends on its economic feasibility.

The four main factors contributing to the total cost of a computer control scheme are: (1) computer system costs; (2) instrumentation costs;

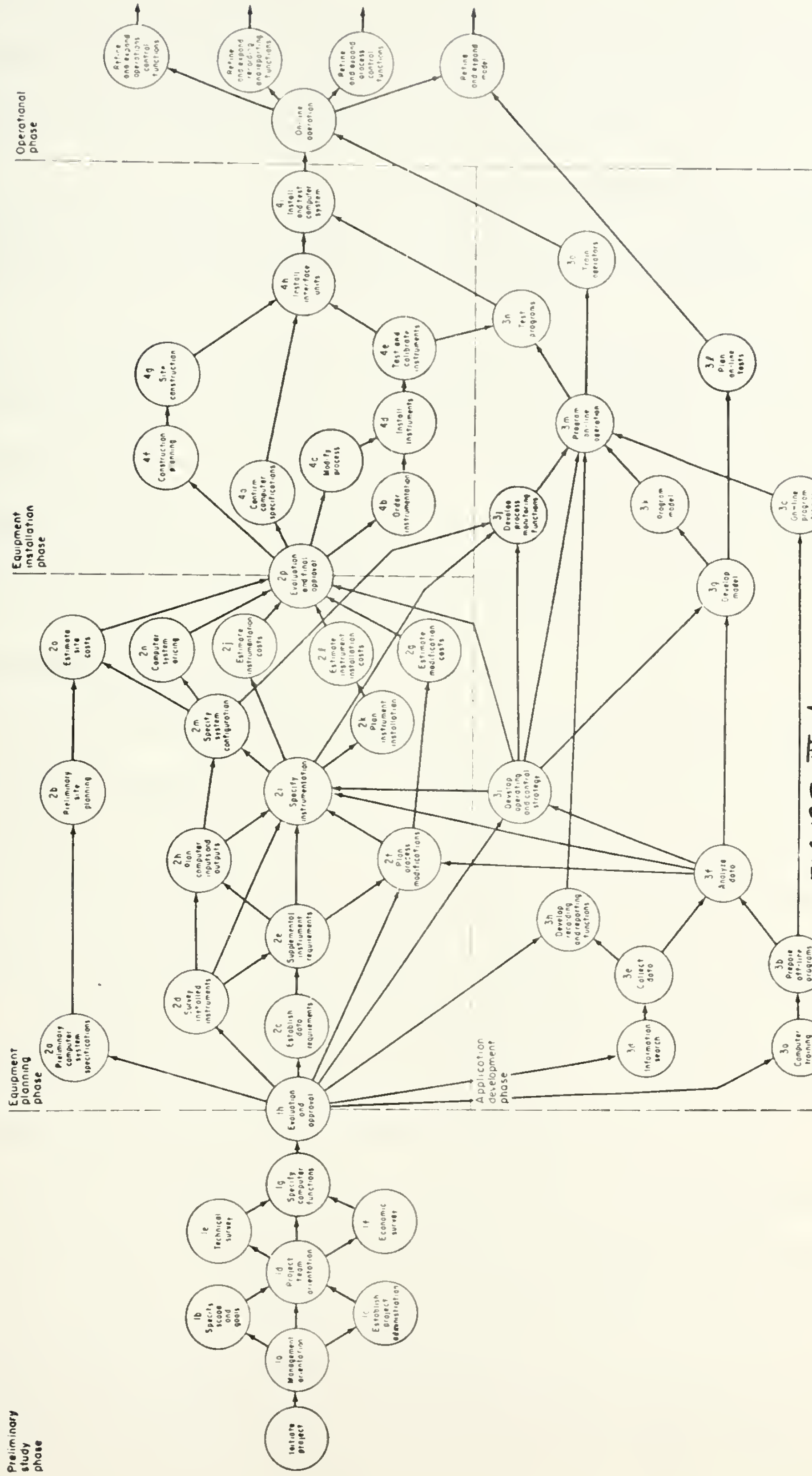
Preliminary study phase
Equipment planning phase
Equipment installation phase
Operational phase
Application development phase
Initiate project
1a Management orientation
1b Specify scope and goals
1c Establish project administration
1d Project team orientation
1e Technical survey
1f Economic survey
1g Specify computer functions
1h Evaluation and approval
2a Preliminary computer system specifications
2b Preliminary site planning
2c Establish data requirements
2d Survey installed instruments
2e Supplemental instrument requirements
2f Plan process modifications
2g Estimate modification costs
2h Plan computer inputs and outputs
2i Specify instrumentation
2j Estimate instrumentation costs
2k Plan instrument installation
2l Estimate instrument installation costs
2m Specify system configuration
2n Computer system pricing
2o Estimate site costs
2p Evaluation and final approval
3a Computer training
3b Prepare off-line programs
3c On-line program training
3d Information search
3e Collect data
3f Analyze data
3g Develop model
3h Develop recording and reporting functions
3i Develop operating and control strategy
3j Develop process monitoring functions
3k Program model
3l Plan on-line tests
3m Program on-line operation
3n Test programs
3o Train operators
4a Confirm computer specifications
4b Order instrumentation
4c Modify process
4d Install instruments
4e Test and calibrate instruments
4f Construction planning
4g Site construction
4h Install interface units
4i Install and test computer system
On-line operation
Refine and expand operations control functions
Refine and expand recording and reporting functions
Refine and expand process control functions
Refine and expand model

FIGURE VII-1

Arrow diagram for a computer control application project.

(3) installation costs; and (4) project staffing costs. Incentives (positive cash flows) include possible reduced manning levels, reduced operating costs, and increased availability of the ship.

Current evaluation techniques, whether of the net present value, payback or other type must then be applied so that a decision can be made.

From at least a hardware standpoint, the future of computer control is promising. Historically, the price of computers and associated hardware have been decreasing at a significant rate. This coupled with factors of increased operator experience and improved equipment reliability should generate new interest in computer controlled systems.

4. Regulatory Body Requirements

The various major regulatory agencies associated with the marine field have established recommendations (i.e., requirements for ship certification) for designers in developing automated installations. Although the regulatory bodies have varied prime interests which to some extent are reflected in their requirements, the feature of safety is common and emphasized in all. Integrity of control and reliability are stressed; all require that manual operating capability be retained as backup for the automatic systems and for use in startup and shutdown of the plant. All urge the definition of proper protective functions for the whole machinery system, but the degree of explicitness varies as to minimum requirements for major plant elements. A brief comparison of the significant differences in emphasis by the major agencies follows.

Det norske Veritas

This agency concerns itself with three major areas of automation: (1) automatic control systems designed to keep plant parameters within control limits; (2) monitoring and informational display systems; (3) remote control (i.e., bridge or control room) of machinery. For unattended operation, specific recommendations are directed toward alarm system responsibility, control transfer and communications. Automatic recovery is not a part of the system in the event of shutdown or reduced capability.

U. S. Coast Guard

The emphasis by this agency is directed toward fire and flooding alarms. In addition, Coast Guard regulations permit limited automatic startup after shutdown, thus moving further into the area of automatic recovery. Alarm monitoring responsibility is directed to the engineers' quarters rather than to the bridge watchstander.

American Bureau of Shipping

ABS regulations generally are similar to those of Det norske Veritas. Alarm monitoring is directed to the engineers' quarters. Control, monitoring, and alarm functions are spelled out in considerable detail.

Lloyd's Register of Shipping

Lloyd's requirements, though brief, emphasize safety of ship and machinery. Automatic systems, when installed, must protect the plant, bring faults to the engineer's attention, and notify the bridge watch of any degradation of propulsion capability.

References (5) through (10) contain more detailed information on regulatory

body requirements.

CHAPTER VI.

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CHAPTER VII.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Automation of slow speed diesel engine propulsion plants has progressed substantially since its introduction in the early 1960's. Today one could say that automation, in one form or another, is widely used in the marine field. On the other hand, control using digital computers has been successfully applied, but its use is far from extensive.

As in any practical situation, the economics of digital control have to some large degree influenced the magnitude of its usage thus far, and will continue to do so in the future. If current economic trends are a guide, the decreasing hardware costs (combined with increasing operator experience and reliability) suggest increased application of digital control techniques.

Design of a computer control system is far from a simple task. It requires application of skills which cross the normal disciplinary lines. Complete system design, installation and subsequent operation constitutes a task of proportions beyond the limited scope of this project.

Direct digital control is a technically feasible scheme, and one that offers several distinct advantages. Hardware of requisite accuracy, durability, compatibility, and reliability at reasonable cost seems to be available. There are several whole plant digital control packages already at sea and a far greater number of industrial packages.

Recommendations

Since this project was limited in scope, further development is necessary, including:

a. Investigation of complete machinery plant control (including auxiliary generators, distilling plants, etc.) using DDC.

b. Inclusion of additional features such as startup after long duration shutdown, heavy fuel operation, and the like.

c. Economic analysis of control alternatives including DDC.

APPENDIX A.

Diesel Particulars

Test bed data for the B/W 7K98FF engine are shown in Figure A-1. The ideal diesel power-speed curves for constant fuel settings are derived from this and are shown in Figure A-2. The torque-speed characteristics are in turn derived from this figure and are shown in Figure A-3. The continuous service rating of the engine is 24,500 metric bhp at 100 rpm and the maximum continuous rating is 26,600 bhp at 103 rpm.

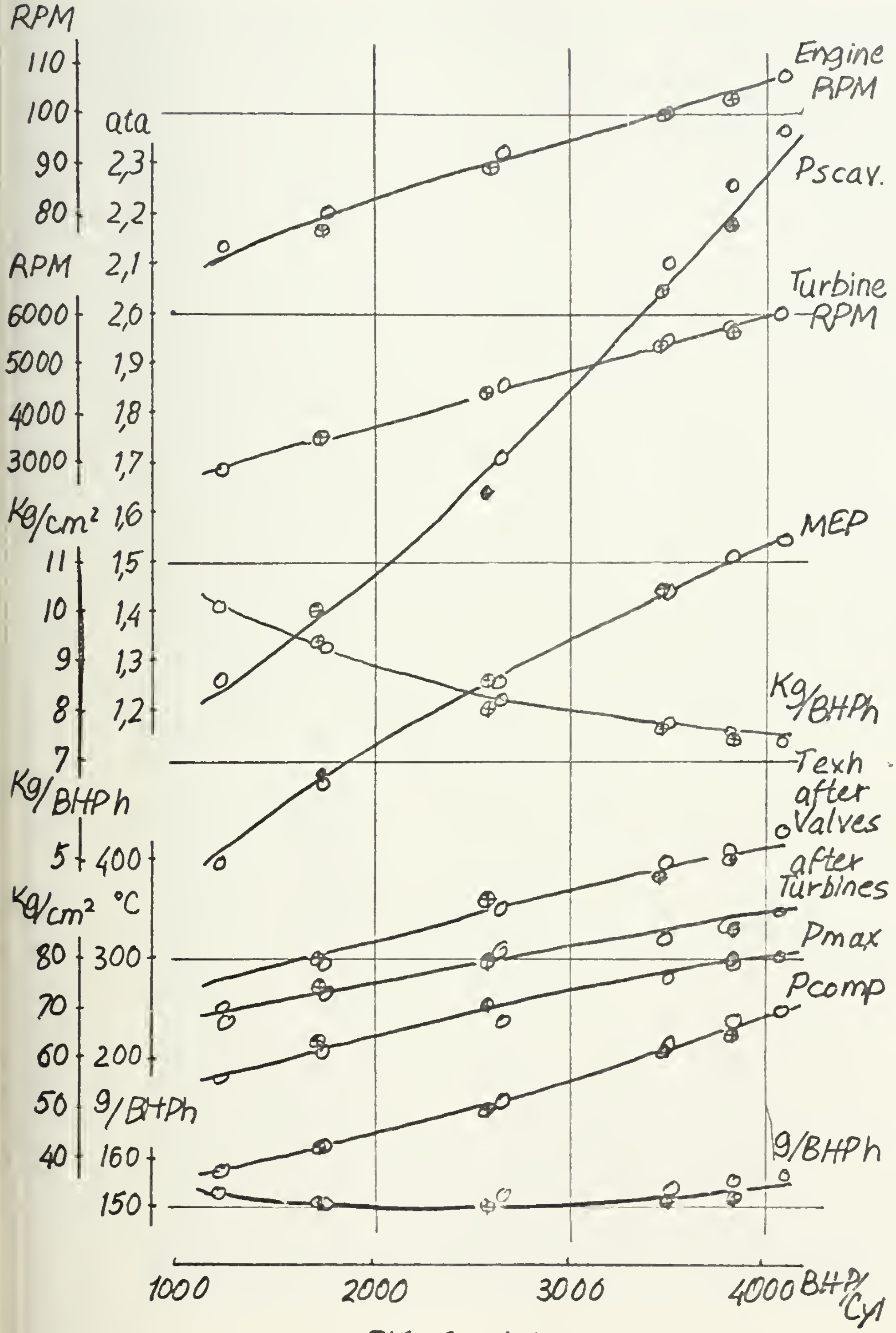

FIGURE A-1

TEST BED RESULTS OF 7K98FF

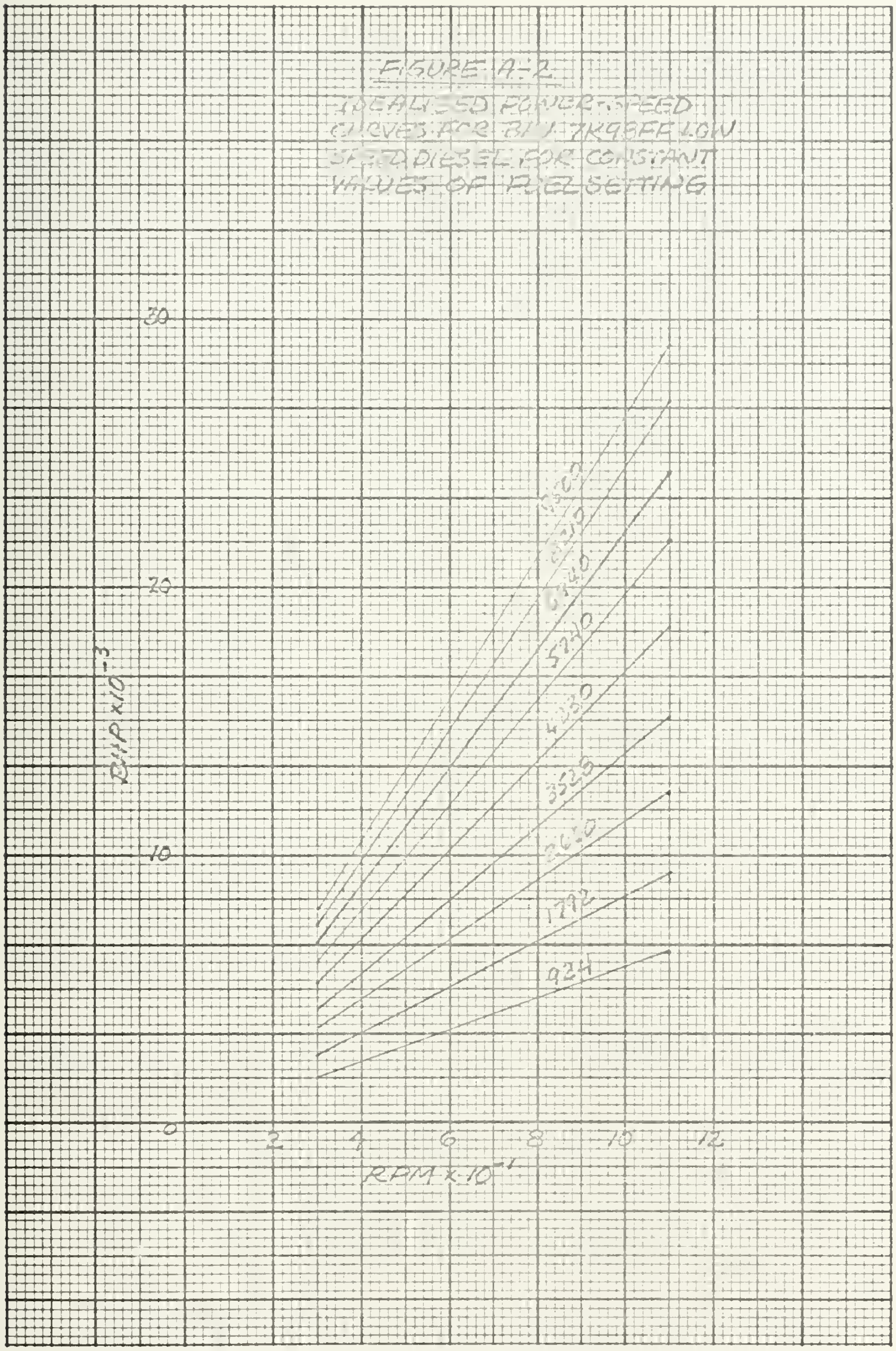

FIGURE A-2
IDEALISED POWER-SPEED CURVES FOR B&W 7K98FF LOW SPEED DIESEL FOR CONSTANT VALUES OF FUEL SETTING

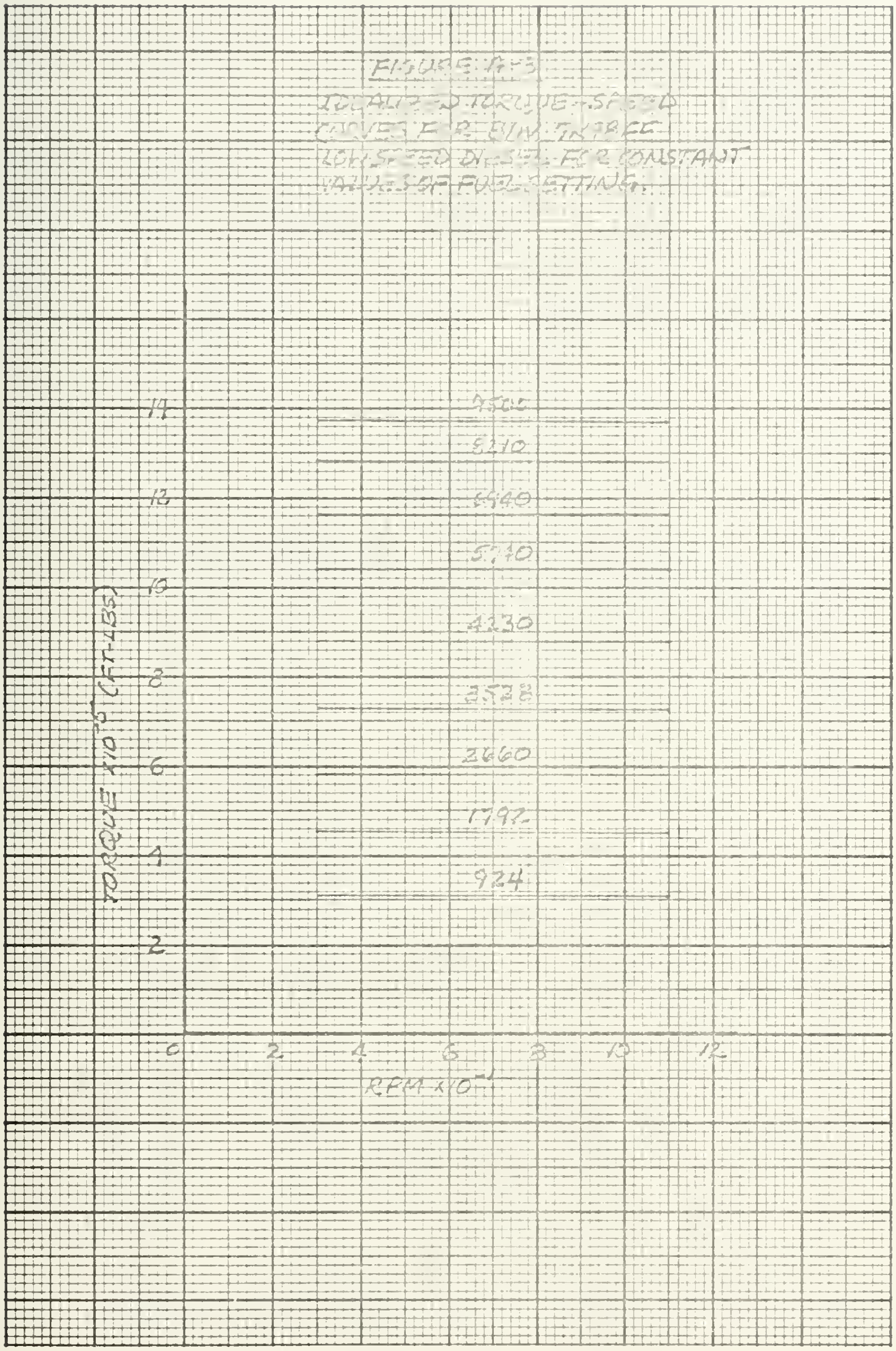

FIGURE A-3

IDEALIZED TORQUE-SPEED CURVES FOR B&W TRIPLE LOW SPEED DIESEL FOR CONSTANT VALUES OF FUEL SETTING.

APPENDIX B.

Program for "Crashback" of the B/W 7K98FF from 12 Kts.

```
      SUBROUTINE FOSIM
C     REVERSING WITH B/W 7K98EF AND FPP
C     INITIAL SPEED IS 12 KTS (20 RPS)
      COMMON T,DT,Y(20),DY(20),STIME,FTIME,NEWDT
C     Y(1) IS RADIAN ANGLE THETA
C     Y(2) IS SHAFT SPEED IN REV PER SEC
C     Y(3) IS DISTANCE
C     Y(4) IS VELOCITY OF SHIP
      IF(NEWDT)1,2,1
C     VA IS PROPELLOR SPEED OF ADVANCE
    1 VA=.96*Y(4)
C     SRPS IS SHAFT ROTATION RATE IN REV/SEC
      SRPS=Y(2)
C     COMPUTE THRUST AND TORQUE COEF
C     CT AND CO ARE THRUST AND TORQUE COEF
      CALL PRPLR (VA,SRPS,CT,CQ)
      DENOM=VA**2+(50.6*Y(2))**2
C     COMPUTE PROPELLOR THRUST
C     Y(5) IS PROPELLOR THRUST
      Y(5)=413.*DENOM*CT
C     COMPUTE PROPELLOR TORQUE
C     Y(6) IS PROPELLOR TORQUE
      Y(6)=9508.*DENOM*CQ
C     PROPELLOR THRUST IS REDUCED BY THRUST DEDUCTION FACTOR
      Y(5)=.98*Y(5)
C     REVERSING AIR IS CUT IN AT 52 RPM (.87 RPS)
C     FIRING SPEED IN REVERSE IS 15 RPM (.25 RPS)
      IF(Y(2).GE..87)GO TO 3
      IF(Y(2).LT..87.AND.Y(2).GT.-.25)GO TO 5
      IF(Y(2).LE.-.25)GO TO 6
      GO TO 4
C     Y(7) IS FUEL SETTING
    5 TORQ=-1000000.
      GO TO 4
C     FIRING SPEED IN REVERSE IS ACHIEVED IN APPROX 150 SEC
    6 Y(7)=924.+2000.*(T-150.)
```

```
      IF(Y(7).GE.8210.)Y(7)=8210.
C     WF IS FUEL SETTING
      WF=Y(7)
      CALL BURME(WF,TORQ)
      TORQ=TORQ*(-1.)
      GO TO 4
C     FUEL RACK GOES TO NO-FUEL POSITION IN .3 SEC
    3 Y(7)=6353.-20000.*T
      IF(Y(7).LE.0.)Y(7)=0.
      WF=Y(7)
      CALL BURYE (WF,TORQ)
C     Y(8) IS DIESEL TORQUE
    4 Y(8)=TORQ
C     RT IS SHIP RESISTANCE AS A FCT OF SHIP'S SPEED
      RT=611.325*Y(4)**2
C     SHAFT COMPUTES SHAFT FRICTION
C     QF IS SHAFT FRICTION TORQUE
      SN=Y(2)
      CALL SHAFT (SN,QF)
    2 DY(1)=Y(2)*6.28
      DY(2)=(TORQ-QF-Y(8))*4.31E-6
      DY(3)=Y(4)
      DY(4)=(Y(5)-RT)*1.437E-7
      IF(Y(4).LE.0.)ETIME=T
      RETURN
      END
```

```
      SUBROUTINE BURMF (WF,TORQ)
C     THIS SUBROUTINE COMPUTES B/W 7K98FF DIESEL TORQUE AS A FUNCTION
C     OF FUEL SETTING
C     INPUT TO THIS PROGRAM IS FUEL SETTING: OUTPUT IS TORQUE
C     TORQUE IS IN FT LBS
C     WHEN WF IS LESS THAN 924. DIESEL IS ACTING AS A COMPRESSOR
      IF(WF.LT.924.)GO TO 6
      IF(WF.EQ.924.)GO TO 7
      IF(WF.LE.1792.)GO TO 8
      IF(WF.LE.2660.)GO TO 9
      IF(WF.LE.3528.)GO TO 10
      IF(WF.LE.4230.)GO TO 11
      IF(WF.LE.5740.)GO TO 12
      IF(WF.LE.6940.)GO TO 13
      IF(WF.LE.8210.)GO TO 14
      IF(WF.LE.9500.)GO TO 15
    6 TORQ=0.
      RETURN
    7 TORQ=311000.
      RETURN
    8 TORQ=311000.+(WF-924.)*160.
      RETURN
    9 TORQ=450000.+(WF-1792.)*155.5
      RETURN
   10 TORQ=585000.+(WF-2660.)*162.
      RETURN
   11 TORQ=726000.+(WF-3528.)*229.
      RETURN
   12 TORQ=887000.+(WF-4230.)*102.
      RETURN
   13 TORQ=1041000.+(WF-5740.)*99.2
      RETURN
   14 TORQ=1160000.+(WF-6940.)*96.7
      RETURN
   15 TORQ=1283000.+(WF-8210.)*73.75
      RETURN
```

END

```
      SUBROUTINE SHAFT (SN,QF)
C     THIS SUBROUTINE COMPUTES SHAFT FRICTION
C     INPUT IS SHAFT ROTATION RATE (SN) IN REV PER SEC
C     OUTPUT IS FRICTION TORQUE (QF) IN FT LBS
      IF(SN.GE.0..AND.SN.LE..417)GO TO 10
      IF(SN.LT.0..AND.SN.GT.(-.417))GO TO 11
      QF=SN*60000.
      RETURN
   10 QF=25000.
      RETURN
   11 QF=-25000.
      RETURN
      END
```

```
      SUBROUTINE PRPLR (VA,SRPS,CT,CQ)
C     THIS SUBROUTINE COMPUTES THRUST AND TORQUE COEF. FOR B4-70 PROP
C     HAVING A PITCH RATIO OF 1.
C     INPUTS ARE PROP SPEED OF ADVANCE (VA) AND PROP ROTATION RATE
C     (SRPS). OUTPUTS ARE THRUST AND TORQUE COEF, CT AND CQ RESPECTIVELY
C     CT=T/(.5*RHO*(3.14/4.)*(D**2)*(VA**2+.7*SRPS*D**2)))
C     CQ=Q/(.5*RHO*(3.14/4.)*(D**3)*(VA**2+.7*SRPS*(D**2)))
C     RHO=FLUID DENSITY
C     VA=PROP SPEED OF ADVANCE
C     SRPS=PROP ROTATION RATE
C     T=THRUST
C     Q=TORQUE
      IF(SRPS.EQ.0..AND.VA.GT.0.)GO TO 10
      IF(SRPS.EQ.0..AND.VA.LT.0.)GO TO 11
C     B IS HYDRODYNAMIC ANGLE OF ATTACK
      B=ATAN(VA/(33.*SRPS))
      IF(SRPS.LT.0.)B=B+3.14
      IF(B.LT.0.)B=B+6.28
      GO TO 12
   10 B=1.57
      GO TO 12
   11 B=4.71
   12 CONTINUE
      CT=.025350+.17820*COS(B)-.74777*SIN(B)+.014674*COS(2.*B)-.013222*S
     1IN(2.*B)+.028054*COS(3.*B)+.10077*SIN(3.*B)-.016323*COS(4.*B)-.011
     2318*SIN(4.*B)-.053041*COS(5.*B)+.047196*SIN(5.*B)+.0060605*COS(6.
     3*B)+.010666*SIN(6.*B)+.036823*COS(7.*B)-.0090239*SIN(7.*B)-.002542
     49*COS(8.*B)-.0078452*SIN(8.*B)-.017680*COS(9.*B)+.022941*SIN(9.*B)
     5+.0027331*COS(10.*B)+.0080787*SIN(10.*B)
      CQ=.024645+.25718*COS(B)-1.1081*SIN(B)+.010056*COS(2.*B)+.0015999*
     1SIN(2.*B)+.065822*COS(3.*B)+.16455*SIN(3.*B)-.022407*COS(4.*B)-.02
     20601*SIN(4.*B)-.078062*COS(5.*B)+.085243*SIN(5.*B)+.0024126*COS(6.
     3*B)+.0087856*SIN(6.*B)+.061475*COS(7.*B)-.031327*SIN(7.*B)-.016065
     4*COS(8.*B)-.0096650*SIN(8.*B)-.033291*COS(9.*B)+.04310*SIN(9.*B)+.
     5012311*COS(10.*B)+.012453*SIN(10.*B)
      CQ=.1*CQ
```

```
RETURN
END
```

APPENDIX C.

HARDWARE SURVEY

SENSORS

Resistance Temperature Detectors

Mfg.	Model	Element	Temp Range	Resistance	Resistance Temp. Coef.
MINCO PROD, INC.	S323	Ni-Fe Alloy	-80°C-230°C	676 ohm @ 25°C	.00518 ohm/ohm/°C
	REMARKS:	Bearing type; meets Navy MILSPEC, but can be used in fluids. Tip sensitive.			
MINCO PROD, INC.	S324	Cu (pure)	-80°C-260°C	10 ohm @ 25°C	.00427 ohm/ohm/°C
	REMARKS:	Bearing type; meets Navy MILSPEC, but can be used in fluids. Tip sensitive. Approx. price $25.			
MINCO PROD, INC	S325	Platinum (pure)	-80°C-260°C	100 ohm @ 25°C	.00392 ohm/ohm/°C
	REMARKS:	Bearing type; meets Navy MILSPEC, but can be used in fluids. Tip sensitive. Approx. price $25.			
MINCO PROD, INC	S326	Ni (pure)	-80°C-260°C	120 ohm @ 25°C	.00672 ohm/ohm/°C
	REMARKS:	Bearing type; meets Navy MILSPEC, but can be used in fluids. Tip sensitive. Approx. price $25.			
UNITED SYSTEMS CORP	540, 541 542	Platinum	-390°F-1000°F	-	-
	REMARKS:	Accuracy to .15°F. Approx. price $114-$185.			

S E N S O R S (cont)

Resistance Temperature Detectors					
Mfg.	Model	Element	Temp Range	Resistance	Resistance Temp. Coef.
McGRAW EDISON	334	Nickel or Platinum	-70-500^{O}F	136 ohm @ 25^{O}C	-
	REMARKS:	Tip sensitive; accuracy ± 1% of resistance at any temp. Low pressure (70 or 300psi).			
McGRAW EDISON	347	Nickel or Platinum	-70-500^{O}F	136 ohm @ 25^{O}C	-
	REMARKS:	Dual winding; tip sensitive, accuracy ± ½% of resistance.			
McGRAW EDISON	327	Nickel or Platinum	-70-450^{O}F	136 ohm @ 25^{O}C	-
	REMARKS:	Miniature type designed to be imbedded in bearing; max. pressure 2500psig.			
McGRAW EDISON	230	Nickel or Platinum	-100^{O}F-572^{O}C	136 ohm @ 25^{O}C	-
	REMARKS:	Stem sensitive; liquid applications; max. pressure 200psig.			
McGRAW EDISON	330	Nickel or Platinum	32^{O}F-752^{O}F	109 ohm @ 25^{O}C	-
	REMARKS:	Stem sensitive; liquid applications; max.pressure 200psig.			

SENSORS (cont)

Resistance Temperature Detectors					
Mfg.	Model	Element	Temp Range	Resistance	Resistance Temp. Coef.
McGRAW EDISON	232, 384	Nickel or Platinum	-94-572^{O}F	98 ohm @ 25^{O}C	-
	REMARKS:	Stem sensitive; liquid applications; max. pressure 200psig.			
McGRAW EDISON	242	Nickel or Platinum	-60-1500^{O}F	109 ohm @ 25^{O}C	-
	REMARKS:	For use at high temperatures; stem sensitive.			
McGRAW EDISON	333	Nickel or Platinum	-70^{O}C-300^{O}C	136 ohm @ 25^{O}C	-
	REMARKS:	For high pressure use; stem sensitive.			
McGRAW EDISON	246, 315	Nickel or Platinum	-70^{O}C-250^{O}C	136 ohm @ 25^{O}C	-
	REMARKS:	Similar to 333 but shorter stem; stem sensitive.			
ROSEMOUNT	104M Series	Platinum	-200^{O}C-800^{O}C	109 ohm @ 25^{O}C	-
	REMARKS:	Tip sensitive. Approx. cost $35.			

SENSORS (cont)

Resistance Temperature Detectors					Resistance Temp.
Mfg.	Model	Element	Temp Range	Resistance	Coef.
ROSEMOUNT	108MB	Platinum	-200°C-225°C	109 ohm @ 25°C	-
	REMARKS:	Tip sensitive.			
ROSEMOUNT	176MA	Platinum	-200°C-500°C	109 ohm @ 25°C	-
	REMARKS:	Fast response (.2 sec. time constant)			
ROSEMOUNT	108MA	Platinum	-200°C-225°C	109 ohm @ 25°C	-
	REMARKS:	Small, tip sensitive, for use in restricted spaces.			
ROSEMOUNT	77	Platinum	0100°-500°C	109 ohm @ 25°C	-
	REMARKS:	Very rugged.			

S E N S O R S (cont)

Thermocouples				Approx.	Approx.
Mfg.	Model	Element	Temp Range	Sensitivity	Price
MINCO	TC315	Chromel-Alumel	$-18^{\circ}C-260^{\circ}C$	$.022MV/^{\circ}F$	$14
	REMARKS:	Bearing type			
MINCO	TC316	Chromel-Constantan	$-184^{\circ}C-260^{\circ}C$	$.038MV/^{\circ}F$	$14
	REMARKS:	Bearing type			
MINCO	TC317	Iron-Constantan	$-18^{\circ}C-260^{\circ}C$	$.030MV/^{\circ}F$	$14
	REMARKS:	Bearing type			
MINCO	TC318	Copper-Constantan	$-184^{\circ}C-204^{\circ}C$	$.024MV/^{\circ}F$	$14
	REMARKS:	Bearing type			
UNITED SYSTEMS CORP	590JC	Copper-Constantan	$-190^{\circ}C-760^{\circ}C$	-	-
	REMARKS:	Accuracy to $.1^{\circ}C$			

SENSORS (cont)

Thermocouples				Approx.	Approx.
Mfg.	Model	Element	Temp Range	Sensitivity	Price
UNITED SYSTEMS CORP	590TC	Copper-Constantan	$-190^{\circ}C-400^{\circ}C$	-	-
	REMARKS:	Accuracy to $.1^{\circ}C$.			
UNITED SYSTEMS CORP	590KC	Chromel-Alumel	$0^{\circ}C-1400^{\circ}C$	-	-
	REMARKS:	Accuracy to $.1^{\circ}C$.			
UNITED SYSTEMS CORP	590SC	Platinum-Plat. + 10% Rh	$50^{\circ}C-1600^{\circ}C$	-	-
	REMARKS:	Accuracy to $.1^{\circ}C$.			
UNITED SYSTEMS CORP	590RC	Platinum-Plat. + 13% Rh	$50^{\circ}C-1600^{\circ}C$	-	-
	REMARKS:	Accuracy to $1^{\circ}C$.			

SENSORS (cont)

Pressure Transmitters/Transducers

Mfg.	Model	Pressure Range	Accuracy	Output	Operating Temp Range
TYCO INST.	AL	0-5, 0-15, 0-25, 0-20,000psig.	± 1% FSO	4-20 ma (DC) into 100-600 ohm loop resistance	0-200°F
TYCO INST.	AF	0-5, 0-15, 0-25, 0-20,000psig.	± 1% FSO	5.0 VDC	0-200°F
TYCO INST.	AB	0-5, 0-15, 0-25, 0-20,000psig.	± 1% FSO	5.0 VDC	-65°F-200°F
TYCO INST.	HFA & HFH	0-100, 0-200, 0-10,000	.5% FS	100 MV	-65°F-300°F
	REMARKS:	Minature sensors; can be used in high frequency applications.			
TYCO INST.	MPA	0-25, 0-50, 0-5,000	depends on range	-	-65°F-250°F
	REMARKS:	High accuracy sensor.			
ROSEMOUNT	1151GP	0-5 in H_2O 0-1000psig.	.25% of calibrated range	4-50 ma (DC)	-20°F-200°F
	REMARKS:	Approximate cost $570.			

S E N S O R S (cont)

Pressure Transmitters/Transducers

Mfg.	Model	Pressure Range	Accuracy	Output	Operating Temp Range
TELEDYNE TABER	206	0-300, 0-500, 0-5000psig.	.25% of FS	30 MV	-100°F-250°F
	REMARKS:	The company makes a wide variety of very accurate small sized rugged transducers.			
TELEDYNE TABER	217	0-100, 0-150, 0-200psig.	.25% of FS	30 MV	-100°F-250°F
	REMARKS:	The company makes a wide variety of very accurate small sized rugged transducers.			
TELEDYNE TABER	226	0-300, 0-2000psig.	.25% of FS	30 MV	-100-250°F
TELEDYNE TABER	254	0-15, 0-20, 0-100psig.	.25% of FS	30 MV	-100-250°F

SENSORS (cont)

Differential Pressure			System		
Mfg.	Model	Range	Pressure	Accuracy	Type
MERIAM INSTRUMENT	1020	0-50" H_2O 0-400psi	up to 3000psi	½-1% full scale	Bellows
MERIAM INSTRUMENT	1080	0-20" H_2O 0-300" H_2O	-	-	Bellows
	REMARKS:	Particularly suitable for low differential pressures; ambient temperature range -60° to + 200°F.			
ROSEMONT	1151 DP	0-5,30 0-750" H_2O also 0-17psid 0-1000psid	up to 2000psig	.2% of calibrated span	Capacitance sensing
	REMARKS:	Approximate cost $600.			
SCHUMBERGER	"Themis"	.02-43psi in 5 ranges	up to 4300psi	.15%	Force-balance
	REMARKS:	Can also be used to measure absolute pressure or flow; contains own electronic amplifier.			

SENSORS (cont)

Liquid Level

Mfg.	Model	Range	Accuracy	Max Temp	Remarks
ROSEMOUNT	1151LL	0-25,150 0-750 in H_2O	.25% of calibrated span	200°F	Approx. cost $700.

Flame/Smoke Detectors

Mfg.	Model	Principle	Operating Limits	Remarks
McGRAW EDISON	Sanner P/N 42882 Flame Switch 424	Ultraviolet	-40°F-200°F	Used on ships

Displacement Probes

Mfg.	Model	Linear Measuring Range	Freq. Range	Environmental Limits
BENTLEY NEVADA	Type 300	Approx. 50 mils	$0\text{-}10^6$rpm	-50°F-350°F
	REMARKS:	A proximity type probe that provides shaft radial & thrust vibration amplitudes, frequency & phase angle. Used with oscillator/detector from Bentley Nevada.		
BENTLEY NEVADA	Seismoprobe 5150	Approx. 50 mils	a) 900-9000 rpm b) 1500-60,000 rpm	0-350°F
	REMARKS:	Similar to above but case mounted.		

SENSORS (cont)

Torque Meter

Mfg.	Model	Output	Principle
ASEA	"TORDUCTOR"	Approximately 10VDC	Measures the change in permeability of the shaft.

REMARKS: Over 300 units have been installed aboard ships; cost approximately $6,000/shaft. ASEA also sells a power meter based on the standard torque meter.

Thrustmeter

Mfg.	Model	Output	Principle
ASEA	-	0-1MADC or 10VDC	Load cell

REMARKS: Approximate cost $10,000/shaft.

MULTIPLEXERS AND A/D OR D/A CONVERTERS

Mfg.	Model	Number of Points	Operating Temp.	Inputs	Accuracy	Sample Rate	Output
AMERICAN MULTIPLEX SYSTEMS	MUX-2000	68-544 (Super MUX 2000 can go to over 8000)	0-55°C	0-5 or 1-5 VDC; 1-5 10-50ma	.15%FS	Max. 1500 samples/sec	Up to 4, 2 digit (8 bit BCD) 0-10VDC, 5ma
	REMARKS:	Unit also performs A/D conversion					
DIRECT DIGITAL INDUS.	DIGICABLE F(DIA)	8-16/unit expandable	0-75°C	8 bit	.1%FS	Up to 8000 points/sec	0-10V or 4-20ma 0-100ma
	REMARKS:	Performs D/A conversion; designed for computer interface.					
DIRECT DIGITAL INDUS.	DIGICABLE F(AID)	8-lb/unit expandable	0-70°C	± 5V;0-10V	.1%FS	Up to 8000 points/sec	8 bit digital natural binary
	REMARKS:	Performs A/D conversion designed for computer interface.					
DATA TECHNOLOGY	Miniverter MADC series	up to 256	0-50°C	± 10V	.1%FS	Throughput rate can be greater than 200KHZ	10 bit binary 12 bit binary 3 digit BCD
	REMARKS:	Multiplexer and A/D conversion; D/A modules also available.					

MULTIPLEXERS AND A/D OR D/A CONVERTERS (cont)

Mfg.	Model	Number of Points	Operating Temp	Inputs	Accuracy	Sample Rate	Output
DATA TECHNOLOGY	M-DAC	4 per module	0-50°C	Logical "1" :25-5.0V Logical "0" :0-.5V	± 5MV	Throughput rate up to 100KHZ	± 10V, up to 10ma
	REMARKS:	Performs D/A conversion.					
I/C ENGINEERING CORP	Uniplex 600 System	Up to 4864	-30°C-70°C	0-5V	.35%FS	8 bit: 200/sec 12 bit: 120/sec; contact status 60,000/sec	4-20ma 0-5V
	REMARKS:	Performs analog input multiplexing, A/D conversion, and also D/A for analog controllers.					

MULTIPLEXERS/SCANNERS

Mfg.	Model	Channels	Scan Intervals	Remarks
VIDAR	606	10-1000	10ms, 100ms, or 1 sec	Signal conditioning equipment available.
VIDAR	5500/6500	Up to 1024	-	Can function as computer front end. Alarm monitor available.

I/O DEVICES

Teletypes				
Mfg.	Model	Speed	Temp. & Humidity	Power/Type
TELETYPE	38	10 characters/ sec 100 words/min	40-110°F 95% max. humidity	110V 60HZ
	REMARKS:	Although this model may not currently be installed on ships, Teletype makes models that are.		
TELETYPE	35	100 wpm	40-110°F 95% max. humidity	110V 60HZ
	REMARKS:	More rugged; built for continuous operation.		
TELETYPE	Inktronic	1200 words/min	40-110°F 10-95% humidity	Electrostatic

I/O DEVICES (cont)

Recorders		No. of		
Mfg.	Model	Channels	Type	Remarks
SCHLUMBERGER	Monorex	1	Potentiometric	Continuous recording; has alarm features.
SCHLUMBERGER	Euromax 288	1-12	Potentiometric	
SCHLUMBERGER	Euromax 400	1-24	Potentiometric	
TRACOR WESTRONICS	S Series D Series M Series	2-24	-	

CRT			
Mfg.	Model	Keyboard	Remarks
APPLIED DIGITAL DATA SYSTEMS	Consul 800 Series Consul 700 Series	yes	Hardface copier available.

DISPLAY

Digital Panel Meters

Mfg.	Model	Range	Accuracy	Approx. Price
UNITED SYSTEMS CORP.	276 Series	0-100MV to 0-999V	.1% of reading ± 1 digit	$134
	REMARKS:	Has programmable functions including scaling, etc.		
UNITED SYSTEMS CORP.	277 Series	±0-200MV ± 0-1000V	.05% of reading ± 1 digit	$149
	REMARKS:	Has programmable functions including scaling, etc.		

DATA LOGGERS

Mfg.	Model	Features	Max. No. of Inputs	Speed
VIDAR	5400	Alarm monitoring, display and data logging	1-1000	43 meas/sec
	REMARKS:	Computer compatible output and/or printed data; programmable.		
VIDAR	600/6403	Data acquisition	1-1024	Up to 20,000 channels/sec
	REMARKS:	Can be interfaced with computer; for high speed, low-level data acquisition.		
DECCA	ISIS 300	Alarm monitoring, display and data logging.	Up to approx 1400	400 inputs/sec
	REMARKS:	Currently used aboard ship; in general DECCA supplies transducers for this system.		
ELECTRONIC MODULES CORP.	Data Span 1000	Alarm monitoring display, data logging and limited control	-	40 points/sec
	REMARKS:	Can be interfaced with computer.		

INTERFACE EQUIPMENT

Pneumatic/Computer Signal Converters

Mfg.	Model	Type	Range	Cost
MOORE PROD	77-16	Elec-Pneumatic	up to 2500ma/ 3-15psi	$175
	REMARKS:	Have been used with electronic computers.		
MOORE PROD	7806	Pneumatic-Electric	Up to 50ma,5V 3-15psi	$266
	REMARKS:	Have been used with electronic computers.		

Synchro/Digital Converters - Synchro to Digital

Mfg.	Model	Input Ref.	Output
SINGER-KEARFOTT	TRIGAC III and I Series	26Vrms	13 or 14 bit BCD
		Digital to Synchro	
SINGER-KEARFOTT	TRIGAC IV Series	12 bit DTL or TTL	11.8V 400HZ (or 60HZ)

NON-INTERRUPTIBLE POWER SUPPLY (Emergency Power Source)

Mfg.	Model	Standard AC Output	Standard AC Output (15 min-thereafter reduced rating)	Rated AC Output Time With Aux. Battery	Cost
ELGAR CORP	1052	220-240v 10A 49-51HZ	210-230v 4.5A 50HZ	-	$2975
ELGAR CORP	2501	105-130v 50A 59-61HZ	110-120v 21.7A 60HZ	60 min	$3950 (aux. battery additional $1200)

REMARKS: Mfg. has lower capacity models with longer time of output available.

ACTUATORS

Mfg.	Model	Type	Stroke	Air Pressure	Air Consumption	Approx. Cost
ITT HAMMEL-DAHL	Series 50	Pneumatic	$\frac{1}{4}$"-24"	20-100psi	.2scfm @ 40psi	$160
ITT HAMMEL-DAHL	Series B-1020	Pneumatic	-	-	-	$160-$220
	REMARKS:	Rotary; partial arc (38° max); typical use for butterfly or ball valve; torque developed depends on application.				

Mfg.	Model	Type	Voltage	Rated Torque/ Thrust	Standard Output Speed
JORDAN	SM1100 Series	Electric	115VAC or 90VDC	Up to 100 in.lb.	Up to 100rpm
	REMARKS:	Rotary type.			
JORDAN	SM1500 Series	Electric	115VAC or 90VDC	Up to 400 in.lb.	Up to 130rpm
	REMARKS:	Rotary type.			

A C T U A T O R S (cont)

Mfg.	Model	Type	Voltage	Rated Torque/ Thrust	Standard Output Speed
JORDAN	SM1600 Series	Electric	115VAC or 90VDC	Up to 1000 in.lb.	8rpm
	REMARKS:	Rotary type.			
JORDAN	SM5000 Series	Electric	115/220v/ 440v	Up to 10,000 ft.lb.	-
	REMARKS:	90° Rotation.			
JORDAN	LA1100 SERIES	Electric	115VAC or 90VDC	Up to 200 lbs.	Up to 300 in/min
	REMARKS:	Linear			
JORDAN	LA1500 Series	Electric	115VAC or 90VDC	Up to 500 lbs.	Up to 400 in/min
JORDAN	LA2800	Electric	120v/240/ 440VAC or DC	1200 lbs. max	9 in/sec
	REMARKS:	Heavy duty.			

ACTUATORS (cont)

Mfg.	Model	Type	Input Voltage	Torque Rating	Stroke Time
BARBER COLEMAN	-	Rotary, electro-mechanical	28VDC	25 in-lb	90° in; 9.8-16.2 sec at 15 lb-in rating
	REMARKS: Other ratings available.				
MOORE PROD	74G	Pneumatic valve positioner	-	-	-
	REMARKS: For long stroke valves.				

MINI-COMPUTERS

Mfg.	System	Computer	Memory	Cycle time	Remarks
Hewlett-Packard	9600 Series	2100A	8K (expandable to 32K) 16-bits per word.	980nsec	1. Can use FORTRAN, ALGOL or assembler language. 2. 14 channel (expandable to 45) input/output capacity. 3. System 9600 includes optional signal processing equipment and periferals.
Bendix	-	BDX-6200	4K (expandable to 16K) 20-bits per word.	-	1. Controls up to 512 I/O devices. 2. 32 priority interrupt levels expandable to 256. 3. Can use FORTRAN or assembler language.
Systems Engineering Labs	Systems 72	-	32K (expandable to 65K) 16-bits per word.		1. Can use BASIC, FORTRAN and assembler language. 2. 16 channel (expandable to 64) I/O capacity. 3. Up to 384 interrupt levels available.

MINI-COMPUTERS (cont)

Mfg.	System	Computer	Memory	Cycle time	Remarks
					4. Can access up to 256 peripheral devices. 5. optional signal processing and peripherals available.
Systems Engineering Labs	System 85 and 86	-	8K (expandable to 128K) 32-bits per word.	600-850 nsec	Features similar to system 72; up to 128 interrupt levels.
Data General	-	Nova Series	32K words 16-bits per word.	800nsec	A wide variety of optional peripheral equipment is available.
Cincinnati-Milacron	-	CIP 2000 Series	up to 32K bytes; 16-bits per word.	1100nsec	Up to 64 priority interrupts.
IBM	System/7	5010 Series	up to 16K words 16-bits/word.	400nsec	1. Provided with a complete range of peripheral equipment. 2. Maybe coupled with other IBM computers to enhance capability.

PROGRAMMABLE CONTROLLERS

Mfg.	Model	Basic Specifications	Remarks
PROCESS CONTROL, INC	PIC Series	72 input channels, 36 output channels. 8K, 18-bit per word memory. Memory cycle time 900nsec. Memory access time 400nsec.	1. The basic system is expandable. 2. Applications can include data logging, sequence recording, and DDC. 3. Uses standard I/O devices (printers, CRT, etc.) 4. Resembles a mini-computer.
ALLEN-BRADLEY	PMC 1750	62 combined input/output channels; 1152, 8-bit words; 6 msec scan time.	1. The basic system is expandable. 2. Significantly less capability than PIC series.

WHOLE PLANT COMPUTER CONTROL PACKAGE

Currently Used on Ships:

Mfg.	Trade Name	System Functions/Remarks
ASEA	DIESELDAC	1. Alarm Monitoring, printout, trend calculations and display 2. Conditions Checking of machinary, hull, etc. 3. Bridge Control of main engine, control of main engine, control of acceleration, optimizing of stopping distance. 4. Computer Control of various closed loops. 5. Control of Auxiliary Power Systems, including automatic start/stop, load sharing, etc.
IHI	TCM-24D	1. Similar to installation on Seiko-Maru. 2. Features include remote control, automatic start/stop, automatic acceleration, automatic slowdown during casualty conditions, alarm monitoring, etc. 3. Specifically designed for Sulzer RND type engines.
FOXBORO	PCP-88	A DDC package for process control; CPU has min. 12,278, max. 32,768 word memory.
FOXBORO	"PIER" SYSTEM	A DDC package for use in stationary electric power generating plants; functions include: alarm monitoring, logging, trend, analysis, video display; auto machinery start/stop.

WHOLE PLANT COMPUTER CONTROL PACKAGES (cont)

Mfg.	Trade Name	System Functions/Remarks
NORCONTROL	Data Chief	Functions performed include: 1. Monitoring and alarm. 2. Automatic operation of electric power generating plant. 3. Automatic logging. 4. Maintenance information. 5. Bridge control of engine, electronic RPM controller, auto shutdowns and other features when combined with NORCONTROL AUTO CHIEF II. This system is an improved version of that installed in M/S TAIMYR.

145675

Thesis
B7816
Bowman
Direct digital control of marine diesel propulsion plant.

DISPLAY

16 OCT 73

Thesis
B7816
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